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SOIL SCIENCE

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SOIL SCIENCE

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THE ANTAGONISTIC ACTION OF CALCIUM AND IRON SALTS TOWARD OTHER SALTS AS MEASURED BY AMMONIFICATION AND NITRIFICATION

J. E. GREAVES[1]

Department of Bacteriology, Utah Agricultural Experiment Station

Received for publication June 2, 1920

Salts which may occur in soils and those applied to them in various operations influence the physical, chemical and biological nature of the soil. The changed physical and chemical nature may modify the number, species, and physiology of the soil microflora. Hence, the question arises as to what effect a certain fertilizer, soil amendment or soil alkali is going to have and especially how it acts upon the bacterial flora of the soil. This last question is very complex and vital. Its answer necessitates a knowledge of the direct and the indirect reactions into which the chemical enters, also a knowledge of the complex reactions catalyzed by it. Yet these are vital, for the reclaiming of alkali soils and the maintaining of others in a productive condition advances as our knowledge of the intricate changes which the various salts produce within a soil become greater.

Papers have already been published on the relative toxicity of various salts found in or applied to a soil as measured in terms of ammonification (4) and nitrification (5), also upon the stimulating influence of various salts on bacterial activities and the manner in which the stimulation is exerted (6).

It is the purpose of this paper to consider the antitoxic action of calcium and iron salts toward other compounds. Calcium and iron compounds were selected because (a) they exert a marked effect upon plant growth; (b) they influence very materially the physical and chemical properties of the soil; (c) calcium sulfate is used rather extensively in the reclaiming of black alkali land, and (d) they are abundant and comparatively cheap; hence, if found effective they may be used in reclaiming soil which contains moderate quantities of alkalies.

A careful review of the literature has been made. That dealing with the first two phases of the problem has been summarized in the earlier publications (4, 5, 6). It is, therefore, necessary to consider in this paper only briefly the literature dealing with the antagonistic action of salt toward salts.

[1] Most of the analytical work of this study was done by Messrs. Goldthorpe, Carter, and Poulter.

HISTORICAL

Although it has been understood for some time that animals and plants require a balanced nutrient for proper development, yet the modern conception of antagonism is due to Loeb who began publishing in 1901. A general account of his work appears in his "Dynamics of Living Matter" (10). He worked on the development of *Fundulus* eggs in various solutions and found that these eggs are unable to form an embryo if put immediately after fertilization into solution of pure sodium chloride of the same concentration as that in sea-water. This toxicity is reduced if a small definite quantity of the salt of a bivalent metal is added to the sodium chloride. The salt of any bivalent metal is able to produce this effect except those of very poisonous metals, such as mercury. Even such poisonous salts as those of lead are able to produce this result. That this effect is due to the cation was shown by using different salts of the same metals. Trivalent cations were also capable of rendering the toxicity of salts of univalent metals less harmful; but a tetravalent cation, thorium, was found to have only a slight antitoxic effect. The reverse is also true, for monovalent ions were found capable of reducing the toxicity of salts of zinc. A slight antagonism was observed between bivalent cations, such as strontium and magnesium.

The relative quantity of the antitoxic ion that has to be added varies with the concentrations of the toxic solution. Thus with *Fundulus* a concentration of 0.25 *M* sodium chloride is harmless. In a 0.625 *M* sodium chloride solution one bivalent ion is required to render 1,000 sodium ions harmless. It was found impossible to render harmless a solution of sodium chloride above a certain concentration.

It is interesting to note that these antagonistic effects hold only for the eggs and not for the larvae of *Fundulus*. Loeb, therefore, concludes that the antagonistic effects appear only so long as the fish is surrounded by the egg membrane and they are actually due to the two kinds of ions mutually hindering one another's diffusion into the egg.

The work of Loeb on animals has been continued and developed by Osterhout with much ingenuity with regard to plants. His work and that of his contemporaries has been summarized by Atkins (1), Robertson (6), Stiles and Jorgensen (7). The writer, therefore, has no need of making a review of the literature on this subject but will consider only briefly some of the general conclusions which have been reached.

Before ideas on antagonism had taken a definite form Loew (8, 9,) elaborated a theory to account for the toxic properties of magnesium when calcium was not present in sufficient quantity. He supposed calcium to be a necessary constituent of the chlorophyll bodies and nucleus, and when magnesium is present in great excess this takes the place in those bodies that should be occupied by calcium. This causes a structural disturbance on account of which the protein substances cease to be active and death ensues. It will

be observed that this will only explain the need for a balance between calcium and magnesium and is not a general theory of antagonism. In the case of calcium and magnesium the seat of the antagonistic action, according to this theory, is inside the cell in the nucleus and plastids, whereas Osterhout (16) considers that the value of calcium lies in its effect at the surface between the absorbing membrane and the external solution, and is not due to chemical action inside the cell. He, therefore, explains antagonism by assuming that antagonistic substances prevent each other from entering the cell. A difficulty which has been urged against it—that substances slowly penetrate into the cell wall even in a properly balanced solution—he does not consider vital if it is supposed that the antagonistic substances affect certain life processes which control permeability. So long as they are present in the right proportions their effect on these processes is favorable and their penetration into the cell can do no harm. The preservation of normal permeability is regarded as the result rather than the cause of antagonism.

Pauli (17) regards the plasma-membrane as a carrier of ions into the interior of the cell. The plasma-membrane is supposed to form compounds with the ions and by the reversibility of the process the ions enter the cell. From this, Szucs (22) formulates the theory that if there is outside the cell a mixture of salts containing two different ions, both of which are carried in by the same radical of the plasma-membrane, these ions must naturally hinder one another's absorption; each will combine with a part of the plasma-membrane substance which would otherwise be used by the other ion if that alone were present, and so the absorption of both ions is hindered.

Out of the work has grown the idea of physiologically balanced solutions, or as Osterhout conceives it, "normal life is possible only when the necessary salts combine with the colloids of the living substance in a definite ratio."

This conception of antagonism and balanced solutions was first applied to a study of bacteria by Lipman in 1909. In his (11) experiments on the rate of ammonification of *Bacillus subtilis* he showed that there is some antagonism between sodium and magnesium. On the other hand, he (12) found no antagonism but increasing toxicity when magnesium and calcium were combined. Later he (13) demonstrated that there exists, as measured by ammonification, a true antagonism between sodium chloride and sodium carbonate, and between sodium sulfate and sodium carbonate, thus indicating that the cations as well as the anions may at times play a part in antagonism.

Kelley (7), in studying the ammonification and nitrification of certain soils, found no antagonism between magnesium and sodium. However, Lipman and Burgess (14) observed in the case of nitrogen fixation by *Azotobacter chroococcum* an antagonism between sodium and magnesium.

Winslow and Falk (23) have observed antagonistic effects in experiments on *Bacillus coli*. They found that cultures suspended in solutions of sodium chloride or calcium chloride were decreased in number; that higher concentrations produced sterilization of the culture; and that a combination of

sodium chloride and calcium chloride in the molecular proportions of 5 to 1 was favorable to the growth of the organisms.

Shearer (19, 20) has also demonstrated similar effects of salts upon the viability of *Meningococcus* and *Bacillus coli*. He found that a combination of sodium chloride and calcium chloride was favorable to growth, whereas each salt used separately produced a decrease in growth.

Brooks (2) found that, as measured by the rate of respiration of *Bacillus subtilis*, there is a marked antagonism between sodium chloride and calcium chloride, and between potassium chloride and calcium chloride. The antagonism between sodium chloride and potassium chloride is slight, and the antagonism curve shows two maxima.

Later Brooks (3), using the same method and organism, found a well-marked antagonism between magnesium chloride and sodium chloride, and, contrary to the findings of Lipman (12), a very slight antagonism between magnesium and calcium.

EXPERIMENTAL WORK

The soil used in this work, taken from the College Farm, at Logan, Utah, is of a sedimentary nature. It was deposited by streams flowing into the valley, laden with débris derived from the nearby mountains, which are composed largely of quartzite and limestone. A physical and chemical analysis of the soil is given in table 1.

The soil used, therefore, was a sandy loam very high in acid-soluble constituents, but the water-soluble constituents were not excessive. The calcium and magnesium contents were very high and mainly in the form of the carbonate. The soil was well supplied with phosphorus and potassium, and there was a fairly large quantity of iron present. In fact, all of the elements of plant-food were present in abundance, with the exception of nitrogen, which was low. The soil was very productive, and previous work had shown the ammonifying and nitrifying powers of the soil to be about the average for the soils of the arid regions. The nitrogen-fixing powers of the soil were above the average, and previous work had shown it to have an intensely interesting bacterial flora.

Several hundred pounds of the soil were thoroughly mixed, stored in a large box, and kept as near field conditions as possible so that all the work could be done on the same soil. As the soil was needed in the work, portions were brought to the laboratory, air-dried in the dark, then weighed in 100-gm. portions into sterile covered tumblers. To each of these was added 2 gm. of dried blood. The whole was then carefully mixed, and the salt in most cases added from a carefully standardized stock solution. This, together with sufficient sterile distilled water to make the moisture content up to 20 per cent, was thoroughly mixed in the soil. Each series, together with sterile blanks, was incubated at 28° to 30°C. and analyzed for ammonia or nitrates as the case might be.

In every case at least six determinations were made with each concentration of the salt, and in the absence of agreement between determinations, the series was repeated so that the results as herein reported are in every case the average of four or more closely agreeing determinations. Hence, experimental error has been reduced to as near a minimum as possible in this kind of work.

The solutions of the salts were prepared by weighing gram-molecular quantities of Merck's best grade of the respective salts into 1,000 cc. of sterile distilled water and then quantitatively determining the amount present. In those cases in which the analysis showed the concentration wrong, it was corrected, so that we have a definite knowledge of the quantity of salt added to the soil, as the varying results reported by different investigators can in many cases be interpreted by the unknown variation in salts added.

TABLE 1

Physical and chemical composition of soil

PHYSICAL COMPOSITION		CHEMICAL COMPOSITION	
Soil	Per cent	Constituent	Per cent
Coarse sand (above 1 mm.)	17.69	Insoluble matter	66.69
Fine sand (1 to 0.03 mm.)	37.39	Potash (K_2O)	0.55
Coarse silt (0.03 to 0.01 mm.)	15.19	Soda (Na_2O)	0.49
Medium silt (0.01 to 0.003 mm.)	10.36	Lime (CaO)	7.41
Fine silt (0.003 to 0.001 mm.)	10.32	Magnesia (MgO)	4.15
Clay (below 0.001 mm.)		Ferric oxide (Fe_2O_3)	2.93
Moisture and loss	9.05	Alumina (Al_2O_3)	3.49
		Phosphorus pentoxide (P_2O_5)	0.25
		Sulfur trioxide (SO_3)	0.07
		Carbon dioxide (CO_2)	7.62
		Humus	2.18
		Total nitrogen	0.15

The solutions thus prepared were added to the soil and intimately mixed before incubation. Then sodium, potassium, calcium, and magnesium salts were added in quantities sufficient to reduce ammonification or nitrification of the soil between 30 and 50 per cent. The calcium and iron salts were then added in increasing quantities.

Influence of calcium sulfate

Calcium sulfate is a strong soil stimulant and in most cases it greatly increases the crop yield. This is due to a number of factors. First, it may liberate plant-food such as potassium (15) and phosphorus (5); second, it stimulates ammonification (4) to a slight extent and nitrification (6) very markedly; and third, it may under some conditions furnish sulfur to the growing plant. It is often used in the reclaiming of "black alkali" soil, mainly

with the purpose of transforming the black alkali into the white, this latter being more readily leached from the soils. It seems probable that it may at times have an antitoxic effect when applied to alkali soils. Therefore, experiments were conducted in which the following quantities of the respective salts were applied to the soil; sodium sulfate, 2760.2; sodium chloride, 460.0; sodium nitrate, 1840.1; sodium carbonate, 5060.4; magnesium sulfate, 2188.8; magnesium chloride, 972.8; and calcium chloride, 400.64, each stated as parts per million of the cation. This was sufficient to reduce the ammonifying powers of the soil to from 30 to 70 per cent of the original. To this soil was then added calcium sulfate in increasing quantities up to 210 parts per million and the ammonifying powers of the soil determined. The results are given in figure 1.

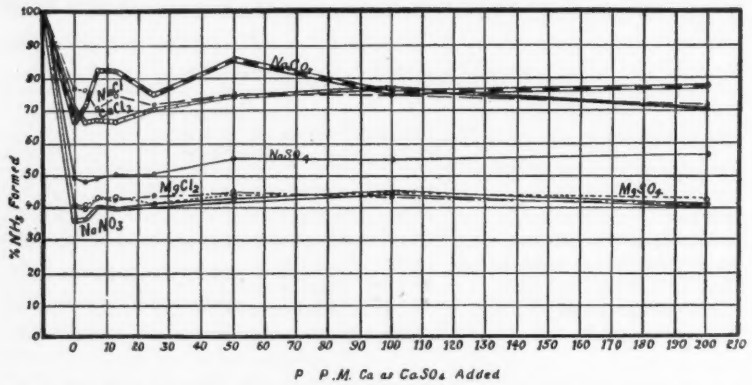

FIG. 1. DIAGRAM SHOWING THE ANTAGONISM OF CALCIUM SULFATE TOWARD SODIUM CHLORIDE, SODIUM CARBONATE, SODIUM SULFATE, SODIUM NITRATE, CALCIUM CHLORIDE, MAGNESIUM CHLORIDE AND MAGNESIUM SULFATE, MEASURED IN TERMS OF AMMONIFICATION

A true antagonism exists between calcium sulfate and each salt, except sodium chloride. This is greatest with sodium carbonate at a concentration of 50 parts per million and is largely due to its rendering insoluble the very toxic black alkali. This cannot be the only effect; otherwise, its antitoxic effect should increase until all the sodium carbonate was neutralized. The toxicity is reduced at this point from 33.4 per cent to only 17.1 per cent. The average antagonistic effect is greater toward the univalent cations than it is toward the bivalent cations. Both the anion and the cation apparently exert an antagonism, and in keeping with the findings of Brooks (3) there is a slight antagonistic effect between calcium and magnesium. However, a person would have to conclude from the magnitude of these results that the main practical value of the application of calcium sulfate to soils is in rendering inert the black alkali. Possibly had the salt concentration been lower more marked results would have been obtained.

Nitrification. The same salts were used in the nitrification test as in the ammonification. The concentrations were as follows: sodium sulfate, 1380.0; sodium chloride, 920.0; sodium nitrate, 460.0; sodium carbonate, 1380.0; magnesium sulfate, 729.6; magnesium chloride, 486.4; and calcium chloride, 1602.56, each stated as parts per million of the cation. This was sufficient to reduce the nitrifying powers of the soil from 100 per cent to 27.26 to 71.16 per cent. The results are given in figure 2.

Two salts show no antagonism, sodium sulfate and calcium chloride. The amount noted in the case of sodium chloride is so small that it may be due to experimental error, thus making it rather certain that there is no antagonism between the anions, sulfate and chloride. There is an antagonism between calcium and magnesium in the case of the nitrifiers as well as the ammonifiers.

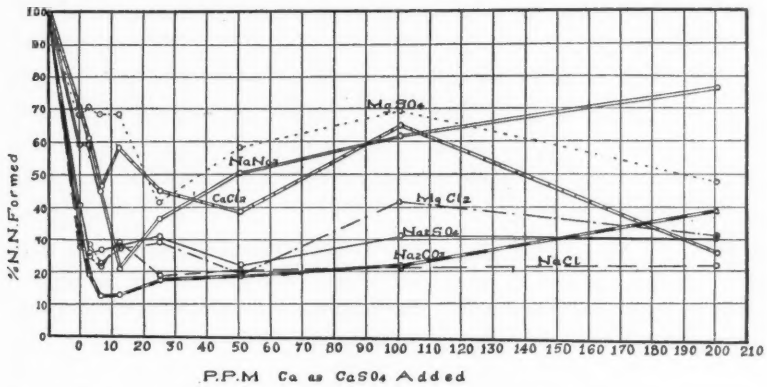

FIG. 2. DIAGRAM SHOWING THE ANTAGONISM OF CALCIUM SULFATE TOWARD SODIUM CHLORIDE, SODIUM CARBONATE, SODIUM SULFATE, SODIUM NITRATE, CALCIUM CHLORIDE, MAGNESIUM CHLORIDE AND MAGNESIUM SULFATE, MEASURED IN TERMS OF NITRIFICATION

It is, however, small in each case. The antitoxic action of the calcium sulfate toward sodium carbonate is not so great as a person might expect, but the results indicate the possibility that if higher concentrations of calcium sulfate had been used the effect would have been more pronounced. The concentration at which the various salts become antitoxic varies markedly. It is evident that the main antagonism is between the cation and not the anion and is slightly more pronounced toward the univalent than the bivalent ions.

Influence of iron salts on ammonification

Iron salts vs. sodium chloride. In this set 460 parts of sodium in the form of sodium chloride was added to the soil. This was sufficient to reduce the ammonium produced to about 75 per cent normal. To these was then added

iron in the form of sulfate, chloride, nitrate and carbonate. The average results from a number of closely agreeing determinations are given in figure 3. The untreated soil has been taken as 100 per cent.

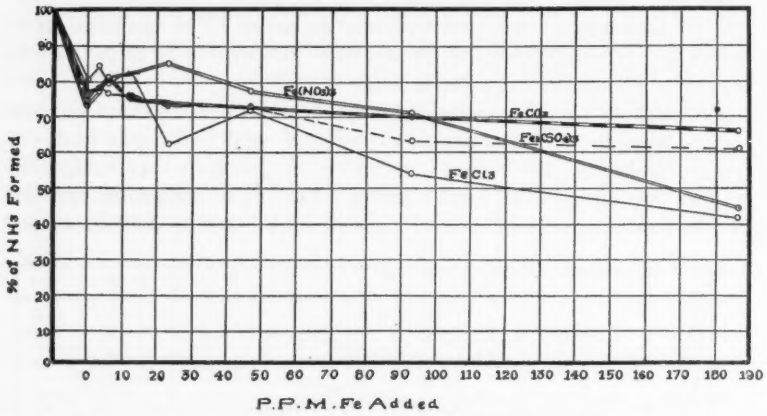

FIG. 3. DIAGRAM SHOWING THE ANTAGONISM OF IRON NITRATE, CARBONATE SULFATE OR CHLORIDE TOWARD SODIUM CHLORIDE, MEASURED IN TERMS OF AMMONIFICATION

Each salt has a slight antagonistic action which is greatest in the case of the nitrate and least in the case of sulfate. The fact that the antagonism does not appear with each salt at the same iron concentration indicates that the anion as well as the cation exerts an action. This, however, is not great for the action is nearly as great in the presence of the common ion chlorine as it is in its absence.

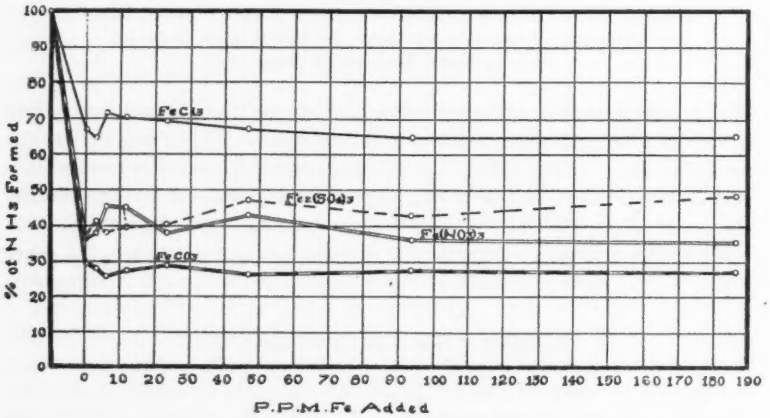

FIG. 4. DIAGRAM SHOWING THE ANTAGONISM OF IRON CHLORIDE SULFATE, NITRATE AND CARBONATE TOWARD SODIUM NITRATE, MEASURED IN TERMS OF AMMONIFICATION

Iron salts vs. sodium nitrate. The same iron salts as used above were tested in combination with sodium nitrate. The results are given in figure 4.

In every case 1840.1 parts per million of sodium in the form of sodium nitrate was added. The iron carbonate had no apparent effect. All others exert an antagonism. This is greatest in the case of the sulfate and least in the case of the chloride. The antagonism is even greater than would appear from these drawings, for when 186 parts of iron is added to the soil in the form of chloride it reduces the ammonifying powers to 72.3 per cent normal; iron sulfate, 84.3 per cent; iron nitrate, 94.8 per cent; and iron carbonate, to 102.1 per cent (4). The increase could not be due to a direct stimulation, for that occurs in much lower iron concentration than the concentration at which antagonism is noted. The iron salts added to a soil even up to 186 parts per million in the presence of sodium nitrate exert no toxic action,

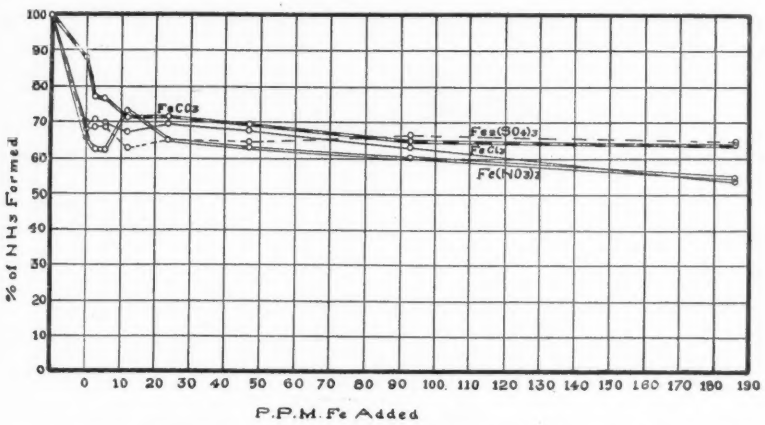

FIG. 5. DIAGRAM SHOWING THE ANTAGONISM OF IRON CARBONATE, SULFATE, CHLORIDE AND NITRATE TOWARD SODIUM SULFATE, MEASURED IN TERMS OF AMMONIFICATION

whereas the same concentration of these salts added to normal soil shows a marked toxic action. The main antagonism is due to the cation, for it is low in the presence of the common anion, carbonate.

Iron salts vs. sodium sulfate. Here the same iron salts were used in the presence of sodium sulfate. The average results for a number of determinations are given in figure 5. The untreated soil is taken as 100 per cent. The quantity of iron added varied from 0 to 186 parts per million. To the soil was added 2760.2 parts per million of sodium in the form of sodium sulfate.

There is no antagonism between the sodium sulfate and iron carbonate and the toxicity of the two salts increases quite rapidly, probably through the formation of sodium carbonate and iron sulfate. Neither the chloride nor the sulfate shows a marked antagonism. The most pronounced antagonism is with the iron nitrate. In this case, however, there is a true antagonism,

for when 11.6 parts per million of iron nitrate was added to this soil (4) its ammonifying powers were 102.8, whereas when added in the presence of the sodium sulfate the ammonifying powers were increased 11 per cent. It is quite evident that in this case the main antagonism is between the anions, sulfate and nitrate. There is less antagonism between the iron salts and sodium sulfate than any of the salts so far considered.

Iron salts vs. sodium carbonate. Sodium carbonate was used in combination with iron carbonate, sulfate, chloride and nitrate. The concentrations varied from 0 to 186 parts per million of iron. To the soil was added 5060.4 parts per million of sodium in the form of sodium carbonate. The results, considering the untreated soil as 100 per cent, are given in figure 6.

There is no antagonism between sodium carbonate and iron chloride. The toxicity of the iron increases just as rapidly in the presence of sodium car-

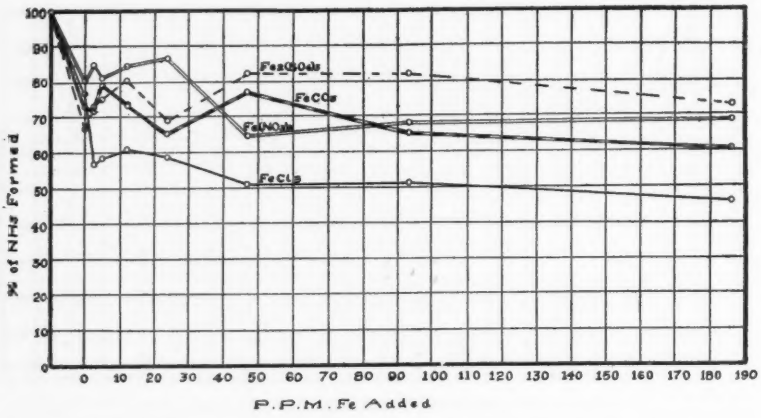

FIG. 6. DIAGRAM SHOWING THE ANTAGONISM OF IRON SULFATE, CARBONATE, NITRATE AND CHLORIDE TOWARD SODIUM CARBONATE, MEASURED IN TERMS OF AMMONIFICATION

bonate as in its absence (4). There is a very marked antagonism between sodium carbonate and iron sulfate. Probably considerable of the benefit resulting from the sulfate is due to its action upon the physical properties of the soil, as the soil is rendered light and porous, thus offsetting the extremely bad puddling effect due to sodium carbonate. Moreover, it is just possible that the iron sulfate would greatly accelerate the leaching of black alkali from the soil. The nitrate and carbonate both exhibit marked antagonistic action toward sodium carbonate.

It is rather evident that there is antagonism between the anion as well as the cation, for iron carbonate offsets the toxic action of sodium carbonate. This also may be due to a better aeration in the presence than in the absence of iron salts. These results give rise to hopes that the iron salts may be used to advantage in reclaiming black alkali. Pot experiments are now in progress, the object of which is to answer this question.

Iron salts vs. calcium chloride. The chloride, sulfate, nitrate, and carbonate of iron were added to the soil in quantities such that the iron added with each salt was the same and varied from 0 to 186 parts per million. To the soil was added 400.64 parts per million of calcium in the form of calcium chloride. The results are given in figure 7.

The antagonistic action in each case was extremely small, thus indicating that the antagonism between calcium and iron, as measured in terms of ammonification, is very small. There is, however, a slight antitoxic action between calcium chloride and each other salt, as we note very little decrease in the ammonia produced as the added iron salts increase. Possibly much more pronounced results would have been obtained had smaller quantities of calcium chloride been used, as it is a well-known fact that the concentration of salts may be high enough to prevent antagonism.

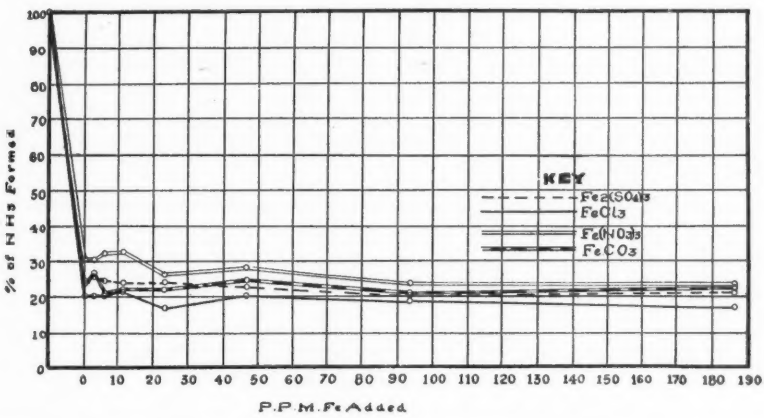

FIG. 7. DIAGRAM SHOWING ANTAGONISM OF IRON SULFATE, CHLORIDE, NITRATE AND CARBONATE TOWARD CALCIUM CHLORIDE, MEASURED IN TERMS OF AMMONIFICATION

Iron salts vs. magnesium chloride. The results obtained when iron salts are used in combination with magnesium chloride are given in figure 8. In combination with iron varying from 0 to 186 parts per million, 972.8 parts per million of magnesium was used.

The only iron salt which increased the ammonification was the nitrate. All the rest ran along about the same, even with increasing quantities of iron. It is, however, quite evident that there is a slight antagonism, for the toxicity of the iron salts does not increase with concentration as is the case when these salts are used singly (4). There is a close resemblance between these results and those obtained with the calcium chloride. There is not so great an antagonism between two bivalent cations as there is between a bivalent and a univalent cation.

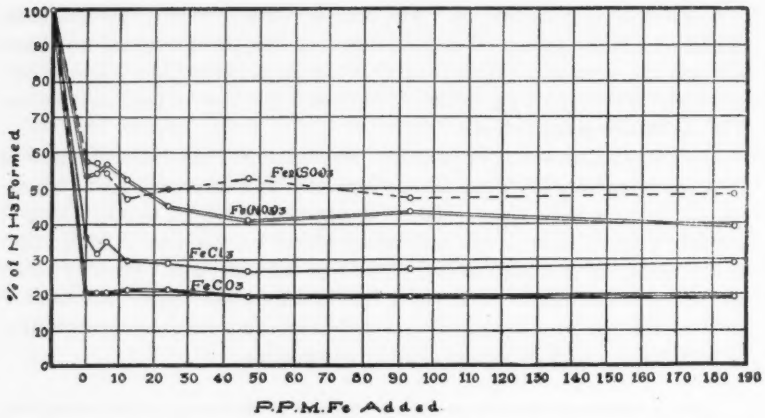

FIG. 8. DIAGRAM SHOWING THE ANTAGONISM OF IRON SULFATE, NITRATE, CHLORIDE AND CARBONATE TOWARD MAGNESIUM CHLORIDE, MEASURED IN TERMS OF AMMONIFICATION

Iron salts vs. magnesium sulfate. The various iron salts were used in combination with 2188.8 parts of magnesium as magnesium chloride. The results are reported in figure 9.

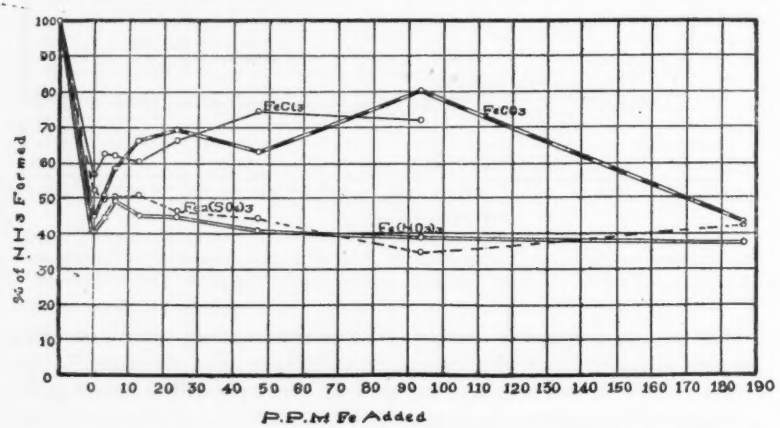

FIG. 9. DIAGRAM SHOWING THE ANTAGONISM OF IRON CHLORIDE, CARBONATE, SULFATE AND NITRATE TOWARD MAGNESIUM SULFATE, MEASURED IN TERMS OF AMMONIFICATION

The sulfate does not increase ammonification nor does it become toxic in the presence of magnesium sulfate as it does when used alone (4). The nitrate has only a slight antagonism as compared with the chloride and the carbonate. These latter increase ammonification 31 and 76 per cent, respectively. The antagonism is higher in the case of these compounds than any of the other compounds tested. The results indicate that the chief antagonism is

between the cations, magnesium and iron. Yet the anion must play a part; otherwise, similar results would have been obtained with magnesium chloride. This must be a true antagonism and not due to better aeration, as was suggested as playing a part with sodium carbonate.

Concentration at which iron salts have the greatest action. The concentration at which the various salts have their greatest antagonistic action varies widely with the salt, as is shown graphically in figure 10.

In most cases the antagonism is greatest at very low concentrations; this with sodium chloride, and with the sulfate or chloride of iron is 2.9 parts per million. Assuming an acre-foot of soil to weigh three million pounds, this would require that only 8.7 pounds per acre of iron in the form of the sulfate or chloride to be applied to a soil. Ususally the antagonism is greatest at very low concentrations. For instance, in five combinations it is where the iron concentration is 2.9 parts per million. This would require the addition of 37.6 pounds of iron sulfate, 30.3 pounds of iron chloride, 44.9 pounds of iron nitrate, or 21.9 pounds of iron carbonate. Such applications to one acre of soil, would not make the cost prohibitive, provided later work shows the antagonism to hold with respect to the higher plants. Six combinations show their best antagonism at 5.8 parts per million which would require 75.2, 60.6, 89.8, and 42.8 pounds per acre if the sulfate, chloride, nitrate, or carbonate, respectively, are applied to the soil. However, to get the greatest antagonism between sodium carbonate and iron sulfate it would require that there be applied to the soil 603 pounds of iron sulfate. This quantity markedly changes the physical properties of the soil and very materially modifies its ammonifying and nitrifying powers. It is slightly toxic to the ammonifiers when applied to a normal soil, but in the presence of sodium carbonate increases ammonification 24 per cent. It is quite likely that it would have a similar effect upon some higher plants. Although the antagonism is mainly between cations, it is evident from these results that the anion plays a part.

Extent of antagonism between various salts. The extent of antagonism existing between various salts is given in figure 11. In each case the ammonifying power of the soil when treated with the salts has been considered as 100 per cent.

Six combinations—magnesium chloride vs. iron sulfate, magnesium sulfate vs. iron sulfate, sodium carbonate vs. iron chloride, magnesium chloride vs. iron chloride, sodium nitrate vs. iron carbonate, and sodium sulfate vs. iron carbonate—depress the ammonifying powers of the soil even in the lowest concentrations tested. In the case of most of the combinations the antagonism is slight, but in the case of the more injurious alkalis it is considerable, amounting in the case of sodium carbonate vs. iron sulfate to 24 per cent. This indicates that it may, under appropriate conditions, have an economic value.

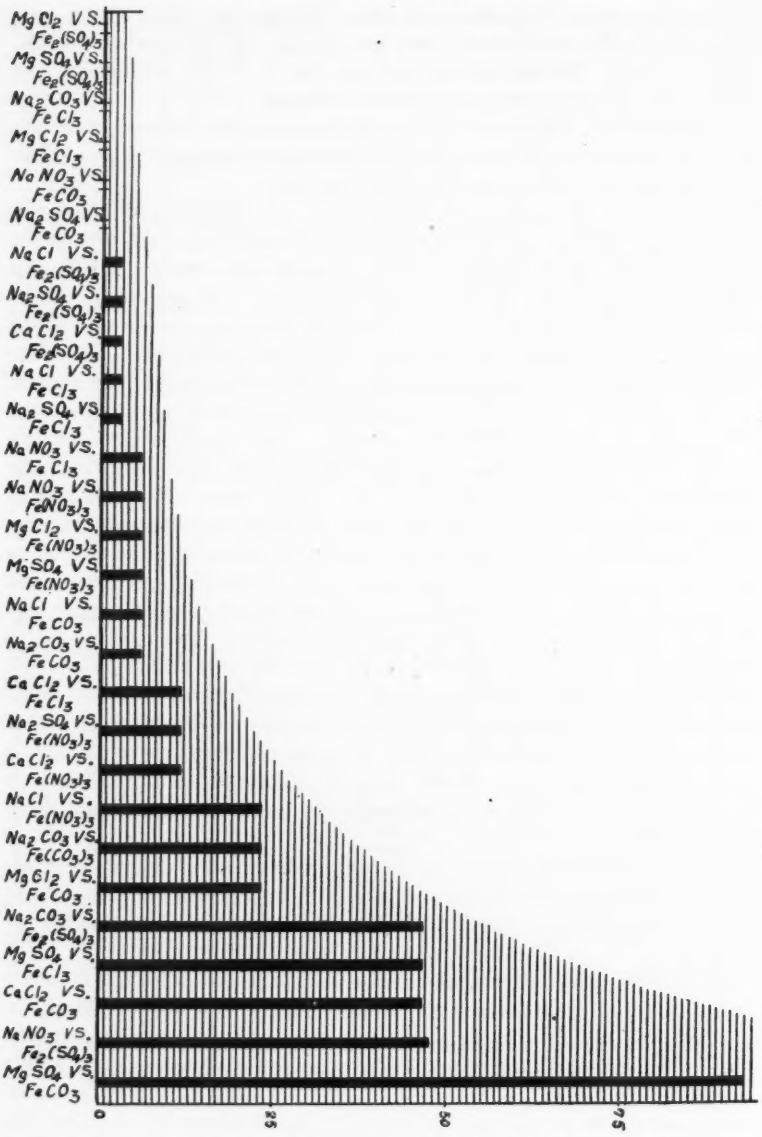
Mg Cl2 VS. Fe2(SO4)3
Mg SO4 VS. Fe2(SO4)3
Na2 CO3 VS. Fe Cl3
Mg Cl2 VS. Fe Cl3
Na NO3 VS. Fe CO3
Na2 SO4 VS. Fe CO3
Na Cl VS. Fe2(SO4)3
Na2 SO4 VS. Fe2(SO4)3
Ca Cl2 VS. Fe2(SO4)3
Na Cl VS. Fe Cl3
Na2 SO4 VS. Fe Cl3
Na NO3 VS. Fe Cl3
Na NO3 VS. Fe(NO3)3
Mg Cl2 VS. Fe(NO3)3
Mg SO4 VS. Fe(NO3)3
Na Cl VS. Fe CO3
Na2 CO3 VS. Fe CO3
Ca Cl2 VS. Fe Cl3
Na2 SO4 VS. Fe(NO3)3
Ca Cl2 VS. Fe(NO3)3
Na Cl VS. Fe(NO3)3
Na2 CO3 VS. Fe(CO3)3
Mg Cl2 VS. Fe CO3
Na2 CO3 VS. Fe2(SO4)3
Mg SO4 VS. Fe Cl3
Ca Cl2 VS. Fe CO3
Na NO3 VS. Fe2(SO4)3
Mg SO4 VS. Fe CO3
0
25
50
75

FIG. 10. DIAGRAM SHOWING THE CONCENTRATION OF IRON SALT WHICH EXERTS THE GREATEST ANTAGONISM TOWARD A SPECIFIC SALT, MEASURED IN TERMS OF AMMONIFICATION

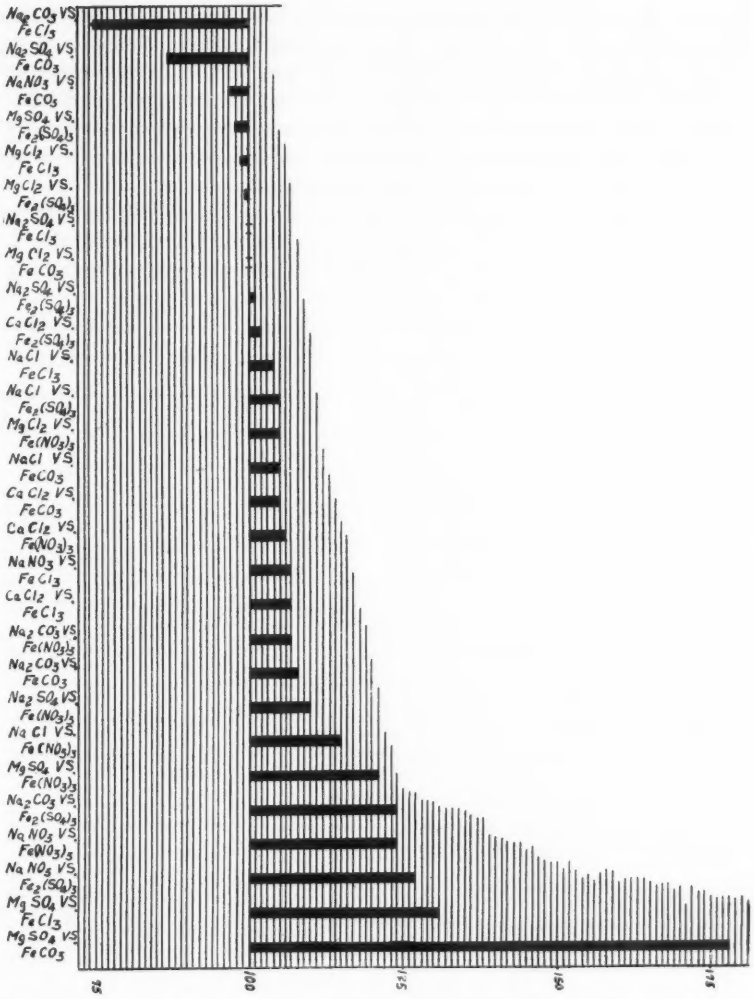

FIG. 11. DIAGRAM SHOWING THE EXTENT OF ANTAGONISM BETWEEN VARIOUS SALTS, MEASURED IN TERMS OF AMMONIFICATION

Nitrification

Iron chloride and iron carbonate stimulate nitrification. Iron sulfate has but little influence, while iron nitrate is a strong poison when used on normal soils (5). But the results obtained on ammonification indicate that the results may be quite different when used in combination with various soil

alkalis. Therefore, determinations were made in which combination of the various iron salts with sodium chloride, sodium sulfate, sodium nitrate, sodium carbonate, magnesium chloride, magnesium sulfate, calcium chloride, or calcium sulfate were used. The general method was that used in ammonification, except incubation lasted 21 days and from four to ten determinations were made. The results as reported consider the untreated soil as producing 100 per cent and are the average of the determinations made.

Iron salts vs. sodium chloride. In combination with iron sulfate, iron nitrate and iron carbonate, 920 parts of sodium in the form of sodium chloride was used. The iron added varied from 0 to 186 parts per million. The results are given in figure 12.

Iron carbonate exerts no antagonism toward sodium chloride as measured by nitrification. The slight gain noted at the higher concentrations is prob-

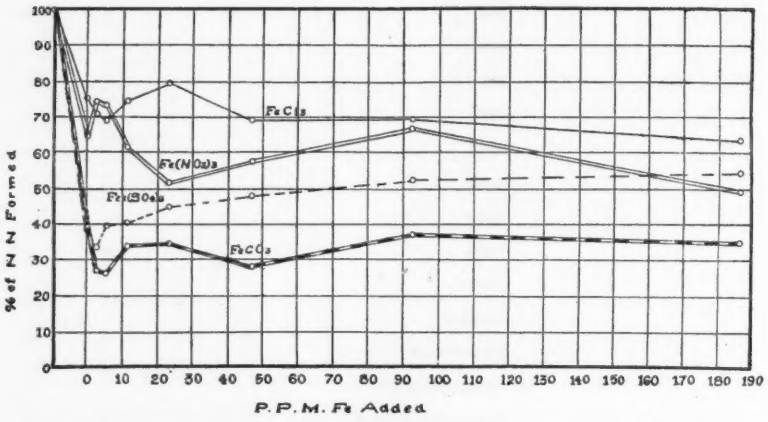

FIG. 12. DIAGRAM SHOWING THE ANTAGONISM OF IRON CHLORIDE, NITRATE, SULFATE AND CARBONATE TOWARD SODIUM CHLORIDE, MEASURED IN TERMS OF NITRIFICATION

ably due to stimulation exerted by the compound, as this compound does stimulate in concentrations from 2.9 up to 1116.9 parts per million. Each of the other salts possesses true antagonistic action, which is greatest with iron sulfate and least with iron nitrate. The variations in concentration at which the iron salts become active make it certain that the anion as well as the cation plays a part. There is also the possibility that a pure physical effect upon the soil may be the main contributing factor. This is borne out by the fact that the iron sulfate is the greatest antagonist but is not so great a stimulant. Although it does not stimulate, yet its antagonistic action increases with concentration. Ferric nitrate, when used alone, is very toxic, yet when used in combination with sodium chloride is not toxic. The chloride and the carbonate are marked soil stimulants as measured in terms of nitrification, yet the carbonate is a better antidote for sodium chloride.

Iron salts vs. sodium nitrate. The results obtained for the iron salts in combination with sodium nitrate are given in figure 13. Four hundred and sixty parts per million of sodium in the form of sodium nitrate was used.

In this set, as in the previous one, iron sulfate possesses the greatest antagonistic action. The nitrate is without effect, whereas the chloride and carbonate neutralized to a slight extent the action of the sodium nitrate. The toxicity of the iron salt increases with concentration even in the presence of sodium nitrate, but not as rapidly as in its absence. The results, together with the appearance of the soil, would lead one to believe that the physical and chemical changes produced in the soil are responsible to a great extent for the neutralizing of the action of the nitrates. But this fact will not materially affect its use in the reclaiming of alkali soils if later tests on soil and

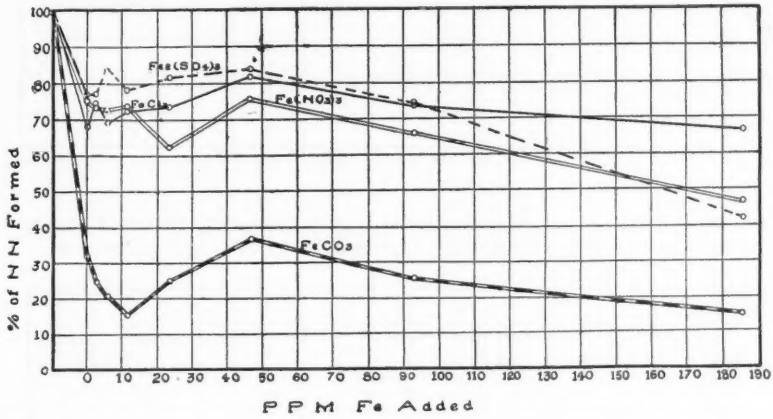

FIG. 13. DIAGRAM SHOWING THE ANTAGONISM OF IRON SULFATE, CHLORIDE, NITRATE AND CARBONATE TOWARD SODIUM NITRATE, MEASURED IN TERMS OF NITRIFICATION

plants show that it increases crop growth or makes the alkali salts more readily leached from the soil.

Iron salts vs. sodium sulfate. The same iron salts were used in combination with sodium sulfate. The results are shown graphically in figure 14. Thirteen hundred and eighty parts per million of sodium in the form of sodium nitrate was used.

The sulfate is without effect, whereas the chloride, nitrate and carbonate all neutralize the toxicity. The antitoxic action of the nitrate and the carbonate is very pronounced. The quantity of iron in the different forms necessary to neutralize varies and is greatest with iron carbonate and least with iron sulfate. Both the anion and cation play a part in the action.

Iron salts vs. sodium carbonate. Such large quantities of sodium carbonate were used in combination with iron chloride and nitrate that little antitoxic

action could be expected, yet the chloride at least possesses a slight antagonistic action, as may be seen from the results given in figure 15.

However, none of the members of this series would lead one to expect great advantages from the use of iron salts on black alkali. Possibly in combina-

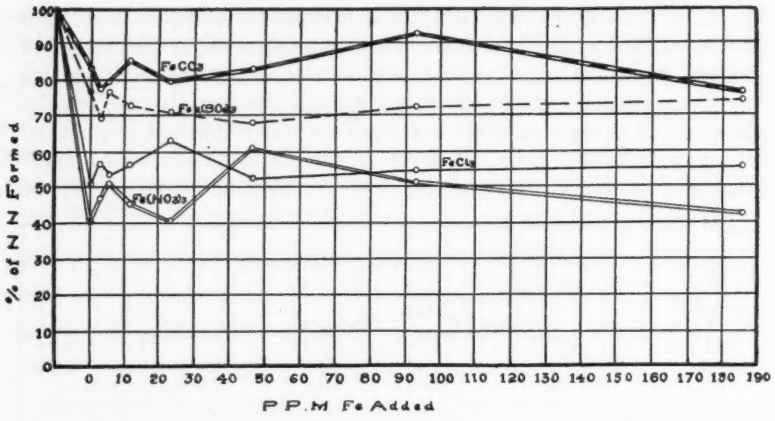

FIG. 14. DIAGRAM SHOWING THE ANTAGONISM OF IRON CARBONATE, SULFATE, CHLORIDE AND NITRATE TOWARD SODIUM SULFATE, MEASURED IN TERMS OF NITRIFICATION

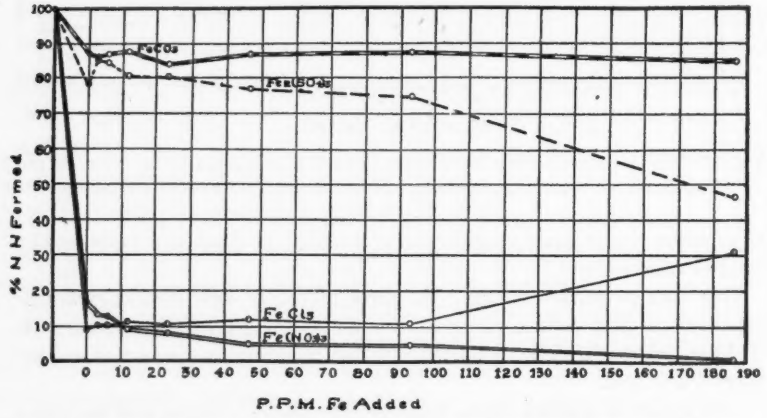

FIG. 15. DIAGRAM SHOWING THE ANTAGONISM OF IRON CARBONATE, SULFATE, CHLORIDE AND NITRATE TOWARD SODIUM CARBONATE, MEASURED IN TERMS OF NITRIFICATION

tion with smaller quantities of sodium carbonate better results would be obtained. But viewing the results with the various sodium salts one must conclude that iron possesses antagonistic action toward sodium, measured both in terms of ammonification and nitrification.

Iron salts vs. magnesium chloride. The various iron salts were used in combination with 486.4 parts of magnesium in the form of magnesium chloride. The results are given in figure 16.

Each of the iron salts acts as a strong antidote to magnesium chloride. The concentration at which they act varies with each specific salt, but in the case of all except the carbonate it is very pronounced. Probably if larger quantities of the carbonate had been used it would have been more pronounced in that case. The concentration at which the iron acts best varies with the negative ion combined with the calcium. This may indicate an antagonism exerted by the anion or a difference in solubility.

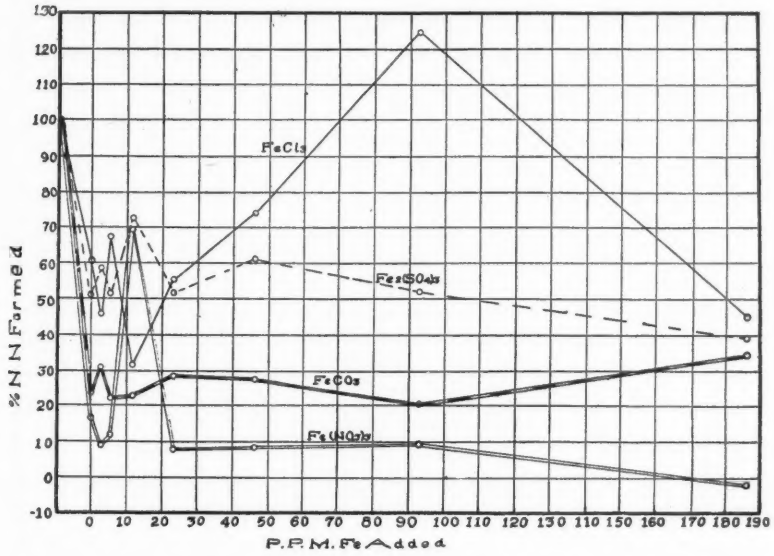

FIG. 16. DIAGRAM SHOWING THE ANTAGONISM OF IRON SULFATE, CARBONATE, NITRATE AND CHLORIDE TOWARD MAGNESIUM CHLORIDE, MEASURED IN TERMS OF NITRIFICATION

If experiments with higher plants bear out these results it is quite possible that iron salts may be used effectively and economically in the reclaiming of alkali soils rich in magnesium salts.

Magnesium sulfate vs. iron salts. Practically the same results were obtained with the sulfate as were obtained with the chloride, as may be seen from figure 17.

The carbonate has only a slight effect. All the other iron compounds show marked antagonism to magnesium sulfate, and in each case the concentration is not far different. There is, however, a difference in degree, for iron sulfate is the best antidote for magnesium sulfate; iron chloride is the best antagonist toward magnesium chloride. This bears out the idea suggested in the last

section that plant work may show it to be effective in combating some forms of alkali under a limited known condition. If effective, it is evident from the low concentration necessary to produce effects that it could be used econom-

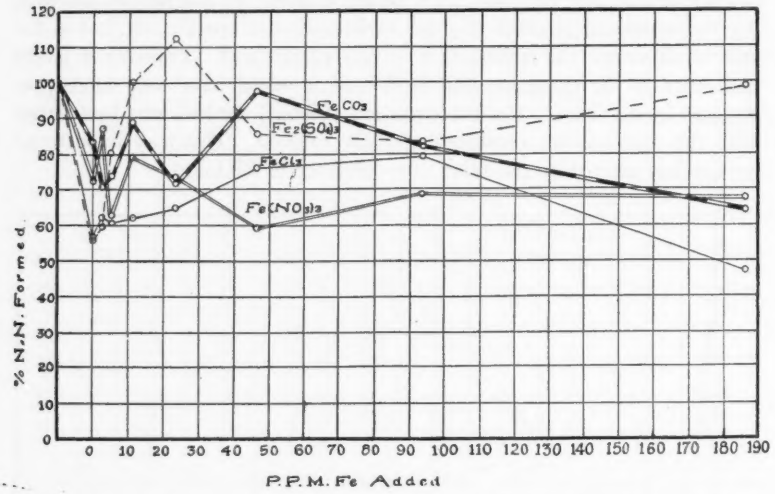

FIG. 17. DIAGRAM SHOWING THE ANTAGONISM OF IRON CARBONATE, SULFATE, CHLORIDE AND NITRATE TOWARD MAGNESIUM SULFATE, MEASURED IN TERMS OF NITRIFICATION

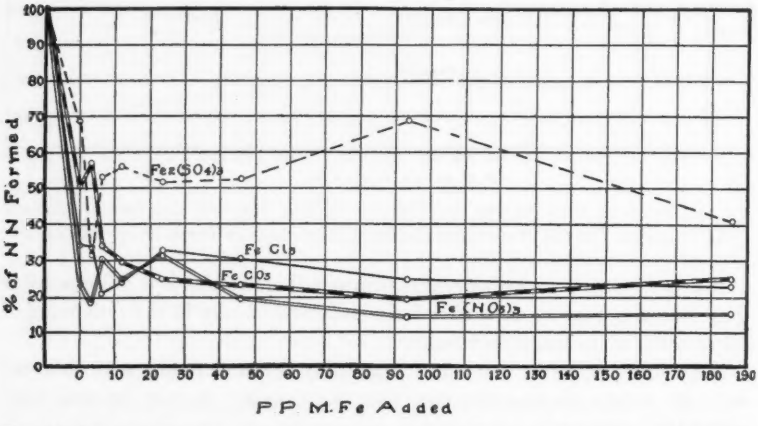

FIG. 18. DIAGRAM SHOWING THE ANTAGONISM OF IRON SULFATE, CHLORIDE, CARBONATE AND NITRATE TOWARD CALCIUM CHLORIDE, MEASURED IN TERMS OF NITRIFICATION

ically. The effect upon the physical condition of the soil was in every case visible and in every case had greatly increased its porosity. This of itself may have played a large part in the change. This, however, cannot be the only factor, for the effect is not directly proportional to the increased aeration.

Iron salts vs. calcium chloride. The results obtained with iron salts in combination with 1602 parts of calcium as calcium chloride are given in figure 18.

Although in none of the concentrations tested did iron sulfate or chloride increase the nitrification over that occurring in the calcium chloride soil, yet it is evident that there must be a slight antagonism since the toxicity of the two salts in combination is not equivalent to that of the two used singly. Iron carbonate, and especially iron nitrate, exert a notable antagonism toward calcium. The results, however, are not as promising with regard to calcium as they are with magnesium.

Concentration at which iron salts have the greatest action. The concentration at which the various iron salts exert their greatest influence varies widely with the iron salt and the alkali, as may be seen from figure 19.

Although in the majority of cases comparatively small quantities of iron are most active as measured in terms of nitrification, yet it has a higher average than is the case with ammonification. This is interesting, for the iron salts are uniformly more toxic to nitrifying (5) organisms than they are to ammonifying organisms (4) when used in the absence of soil alkalis. Only 2.9 parts per million of iron as the sulfate has the greatest influence in combination with the carbonate, whereas 11.6 and 186 parts per million of the carbonate and chloride, respectively, are required. The average quantity of iron in the different forms for greatest antagonism is as follows: iron nitrate, 19.2; iron sulfate, 45.9; iron carbonate, 50.4; and iron chloride, 77.5 parts per million. Should later work on plants show them to have as great a neutralizing influence when measured by plant growth as measured by nitrification, it opens up the possibility of their use in the reclaiming of some alkali soils. The quantities necessary would not be prohibitive in price and they would exert a profound influence upon the physical, chemical, and biological properties of the soil, all of which in so far as our present information goes would be highly beneficial.

The variation in concentration with the different iron salts makes it evident that the anion as well as the cation takes a part in antagonism.

Extent of antagonism between various salts. The extent of antagonism as measured by nitrification between iron salts and soil alkalis is considerable in most cases, as may be seen from figure 20.

Four combinations—sodium carbonate vs. iron nitrate, sodium chloride vs. iron carbonate, calcium chloride vs. iron chloride, and sodium nitrate vs. iron nitrate—depressed nitrification even in the lowest concentrations tested. Sodium sulfate vs. iron sulfate and calcium chloride vs. iron sulfate were without effect, whereas all the remaining combinations stimulated nitrification. In some cases this was high, in a few instances going several hundred times as high in the case of the iron-alkali-treated soil as in the presence of the alkali alone. In those cases where it was highest excessive quantities of the alkali had been added and nitrification was reduced to a great extent; hence, when

expressed in terms of per cent, it appears more pronounced than in the majority of cases. The order of efficiency of the iron salts as antidotes to alkali salts is iron chloride, iron nitrate, iron sulfate, and iron carbonate. The greatest influence is exerted against magnesium chloride and the least toward

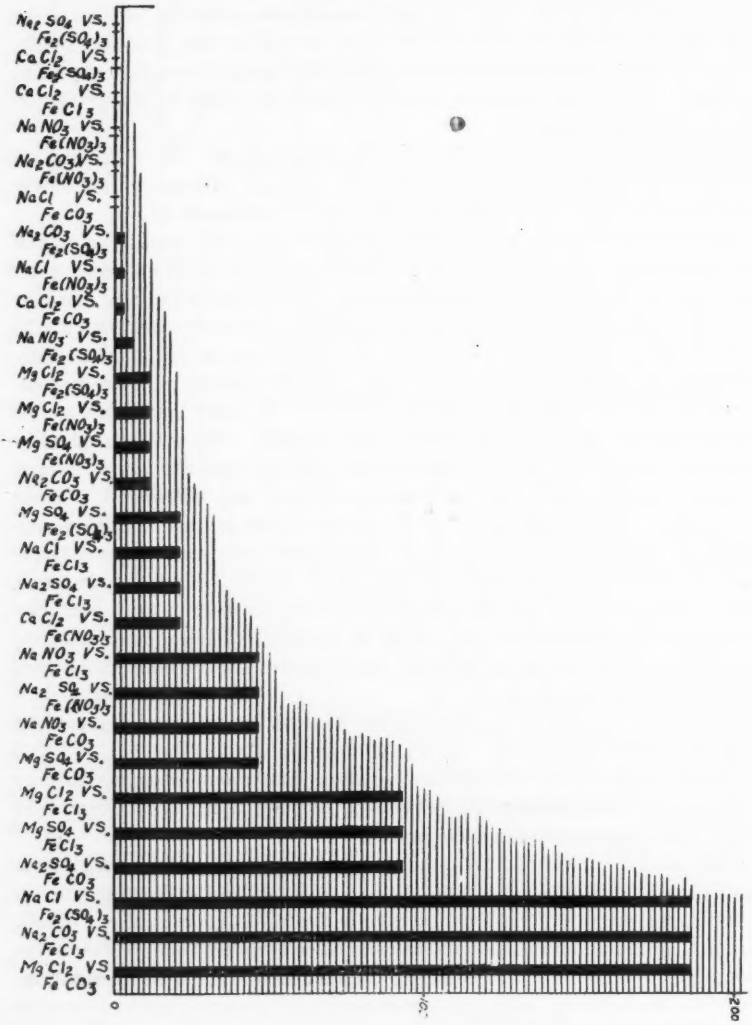
Na2 SO4 VS. Fe2(SO4)3
Ca Cl2 VS. Fe2(SO4)3
Ca Cl2 VS. Fe Cl3
Na NO3 VS. Fe(NO3)3
Na2 CO3 VS. Fe(NO3)3
Na Cl VS. Fe CO3
Na2 CO3 VS. Fe2(SO4)3
Na Cl VS. Fe(NO3)3
Ca Cl2 VS. Fe CO3
Na NO3 VS. Fe2(SO4)3
Mg Cl2 VS. Fe2(SO4)3
Mg Cl2 VS. Fe(NO3)3
Mg SO4 VS. Fe(NO3)3
Na2 CO3 VS. Fe CO3
Mg SO4 VS. Fe2(SO4)3
Na Cl VS. Fe Cl3
Na2 SO4 VS. Fe Cl3
Ca Cl2 VS. Fe(NO3)3
Na NO3 VS. Fe Cl3
Na2 SO4 VS. Fe(NO3)3
Na NO3 VS. Fe CO3
Mg SO4 VS. Fe CO3
Mg Cl2 VS. Fe Cl3
Mg SO4 VS. Fe Cl3
Na2 SO4 VS. Fe CO3
Na Cl VS. Fe2(SO4)3
Na2 CO3 VS. Fe Cl3
Mg Cl2 VS. Fe CO3
0
200

FIG. 19. DIAGRAM SHOWING THE CONCENTRATION AT WHICH VARIOUS IRON SALTS HAVE THE GREATEST ANTAGONISM TOWARD SPECIFIC SALTS, MEASURED IN TERMS OF NITRIFICATION

sodium carbonate. With the exception of iron chloride, the influence exerted against the black alkali is not great. However, all average high enough to suggest that they may have some economic significance for the reclaiming of alkali soils.

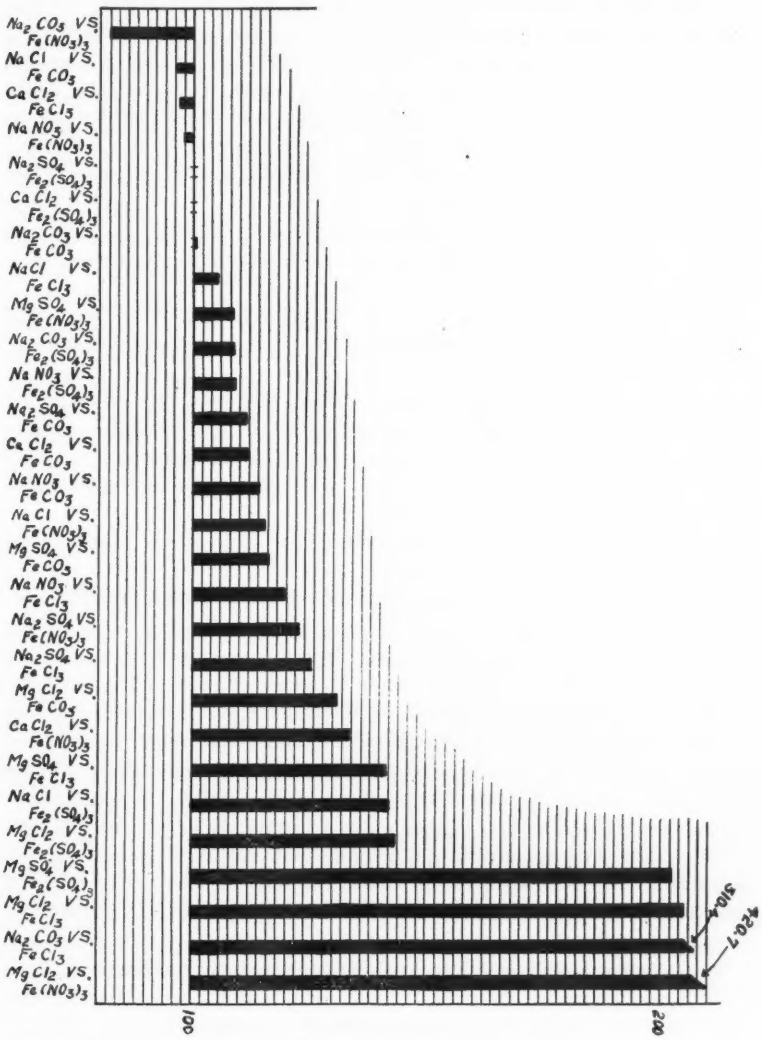

FIG. 20. DIAGRAM SHOWING THE EXTENT OF ANTAGONISM EXERTED BY VARIOUS IRON COMPOUNDS TOWARD OTHER SALTS, MEASURED IN TERMS OF NITRIFICATION

SUMMARY

A true antagonism exists between calcium sulfate and sodium carbonate, sodium nitrate, sodium sulfate, calcium chloride, magnesium chloride, and magnesium sulfate, as measured in terms of ammonification. This is greatest with sodium carbonate and does not occur in the case of sodium chloride. The beneficial effect of calcium sulfate in the presence of sodium carbonate is due to the chemical changing of the sodium carbonate into sodium sulfate and calcium carbonate together with a direct antagonistic action. These results are contrary to those of Lipman (11) and in keeping with those of Brooks (2) in showing an antagonism between calcium and magnesium. This antagonism between calcium and magnesium, although small, also occurs as measured by nitrification.

A similar antagonism exists between these salts, with the exception of sodium sulfate and calcium chloride and calcium sulfate, as measured in terms of nitrification.

These results bear out the findings of Lipman (15) that the anions as well as the cations take a part in antagonism in the case of both ammonifying and nitrifying bacteria.

Iron salts applied to a soil probably change the physical, chemical, and biological nature of that soil. When applied to an alkali soil they usually improve its physical nature, and in this manner offset in a measure the injurious actions of some alkali salts on soils. In addition, some iron salts exert a true antitoxic action toward some alkali salts.

The antagonism is usually greater between monovalent and bivalent ions than it is between two bivalent ions.

As measured in terms of ammonification, a true antagonism was found to exist between sodium sulfate vs. iron sulfate, calcium chloride vs. iron sulfate, sodium chloride vs. iron chloride, sodium chloride vs. iron sulfate, magnesium chloride vs. iron nitrate, sodium chloride vs. iron carbonate, calcium chloride vs. iron carbonate, calcium chloride vs. iron nitrate, sodium nitrate vs. iron chloride, calcium chloride vs. iron chloride, sodium carbonate vs. iron nitrate, sodium carbonate vs. iron carbonate, sodium sulfate vs. iron nitrate, sodium chloride vs. iron nitrate, magnesium sulfate vs. iron nitrate, sodium carbonate vs. iron sulfate, sodium nitrate vs. iron nitrate, sodium nitrate vs. iron sulfate, magnesium sulfate vs. iron chloride, and magnesium sulfate vs. iron carbonate. This was small in the case of the first pair and increased in the order named until the last which neutralized 75 per cent of the toxic effect of magnesium sulfate.

No antagonism was found to exist between sodium carbonate vs. iron chloride, sodium sulfate vs. iron carbonate, sodium nitrate vs. iron carbonate, magnesium sulfate vs. iron sulfate, magnesium chloride vs. iron chloride, magnesium chloride vs. iron sulfate, sodium sulfate vs. iron chloride, and magnesium chloride vs. iron carbonate.

As measured in terms of nitrification, a true antagonism was found to exist between sodium carbonate vs. iron carbonate, sodium chloride vs. iron chloride, magnesium sulfate vs. iron nitrate, sodium carbonate vs. iron sulfate, sodium nitrate vs. iron sulfate, sodium sulfate vs. iron carbonate, calcium chloride vs. iron carbonate, sodium nitrate vs. iron carbonate, sodium chloride vs. iron nitrate, magnesium sulfate vs. iron carbonate, sodium nitrate vs. iron chloride, sodium sulfate vs. iron nitrate, sodium sulfate vs. iron chloride, magnesium chloride vs. iron carbonate, calcium chloride vs. iron nitrate, magnesium sulfate vs. iron chloride, sodium chloride vs. iron sulfate, magnesium chloride vs. iron sulfate, magnesium sulfate vs. iron sulfate, magnesium chloride vs. iron chloride, sodium carbonate vs. iron chloride, and magnesium chloride vs. iron nitrate. This was low in the case of the first pair and increased progressively in the order named up to the last named pair in which the iron nitrate increased the nitrification 420.7 per cent over that soil treated with magnesium-chloride alone.

The quantity of iron required for maximum effect varied with the iron compound and the specific alkali. In no case, however, did the quantity exceed 186 parts per million of iron. Although the greatest influence was exerted by the cations, the anions were not without effect.

If later work shows these salts to have as great an antitoxic action toward alkalis, as measured by higher plants, as has been found to be the case with bacteria they may be used to advantage for the reclaiming of some alkali soils

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A CAPILLARY TRANSMISSION CONSTANT AND METHODS OF DETERMINING IT EXPERIMENTALLY

WILLARD GARDNER

Department of Physics, Utah Agricultural Experiment Station

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INTRODUCTORY

The first part of this article is a general theoretical discussion of soil-moisture movement. Following the suggestion of Briggs (1, 2) and the example of Buckingham (3) and Slichter (6), an attempt has been made to attack the problem from the mathematical point of view, making use of well known methods and theorems of mechanics and hydrodynamics. For the benefit of those who are not familiar with the technical language of physics, it may be stated that the investigation assumes the existence of a characteristic soil constant heretofore undefined, a knowledge of which, together with readily obtained experimental quantities, will give sufficient data for the calculation of the direction and magnitude of the capillary stream. For example, it is well known that moisture may flow upward to the surface of the ground more readily from a water-table 6 feet below the surface than from a water-table 12 feet below, and we might assume offhand that the flow would be double from the 6-foot water-table. It is apparent, of course, that the kind and condition of the soil will be concerned, but for a given soil of given structure, it would no doubt be granted that the magnitude of the stream is determined by the moisture gradient and the moisture density, together with the *character* of the soil. The investigation is directly concerned primarily with the matter of defining this *character* in mathematical language and with methods of measuring it experimentally.

In physics we have numerous relations which are more briefly and precisely stated mathematically, in many cases a comparatively simple equation expressing what would require pages in any other language. We have, for example, a mathematical theory of the flow of heat, the flow of electricity, the flow of liquids, gases, etc., including such "usuable" equations as Ohm's law for electricity, Fourier's law for heat, Poiseuille's law for liquids; and in order to make definite progress in moisture studies, the assumption has been made that we must have a general solution for the law of capillary flow.

A network of electrical conductors might be arranged connecting two electrodes and a corresponding current might be experimentally measured for each branch of the network, and a variation of any of the several factors involved, viz., kind and dimensions of wires, number and kind of branches,

potential difference at the terminals, etc., would give an endless variety of experimental curves, each purporting to illustrate some new law, when in reality the entire problem may be solved on the basis of well known fundamental equations by a knowledge of certain characteristic constants of the metals concerned, together with the dimensions of such wires and the nature of the circuit. Likewise, we might succeed in encumbering the literature with innumerable experimental facts, each purporting to illustrate a new law of moisture flow or moisture distribution, when in reality they are all special cases of some general law. It is granted, of course, that experimental investigation must furnish the ultimate answer to this and any other inquiry of the kind, but we should not fail to recognize the fact that classical physics includes much that has already been verified of universal application and there should be little hesitancy in putting this information to use even in such complex problems as those encountered in the study of soils.

The latter part of the article deals with experimental data obtained from various laboratory and field experiments completed and in process at the Utah Experiment Station, planned very largely on the basis of a tentative solution of the problem which has already been published (5). It is hoped that the methods and results may be of interest to the general reader who does not care to enter into an analysis of the theoretical discussion. It is suggested that the transmission constant should be regarded as analogous to the electrical conductivity of a metal wire or to the thermal conductivity of a furnace wall. In the first case we may obtain the strength of the electric current by measuring the potential difference across the ends of a conducting wire if we know the resistance. In the case of the flow of heat we may determine the rate of loss of energy across a furnace wall by measuring the temperature difference if we know the thermal conductivity. Similarly, we may determine the flow of moisture through a soil by measuring the moisture difference between two adjacent points if we know the capillary transmission constant.

THEORETICAL

Briggs (1, 2) pointed out many years ago that the underlying physical factors concerned in the capillary movement of moisture were the surface tension and the coefficient of viscosity of the liquid, together with the geometrical configuration of a rather complex three-phase soil mass. Buckingham (3) proposed a theoretical solution of the problem, introducing a potential to be determined as a function of the moisture density by measuring the moisture distribution in a column of soil containing moisture in equilibrium under the opposing forces due to gravity and capillarity. Slichter (6) has treated the problem where the liquid-air surface is not concerned. Cameron (4) has written an equation for the rate of ascension of capillary moisture. Widtsoe (7) has recognized a law of capillary flow, although he has not expressed it adquately, nor are his data sufficient for its empirical determination.

Through the inspiration of his work, however, the author (5) has proposed a tentative general solution of the problem differing somewhat in method of attack from those indicated.

The problem may be summarized about as follows:—A sheet of water over the surface of a column of dry "dusty" soil in a closed vessel does not constitute a system in equilibrium. A mere drop on such a surface is likewise unstable. In either case, however, in order to pass to equilibrium it may be necessary for movement to take place primarily by distillation, owing to the fact that a transition without a change of state may involve a path in which conditions of relative equilibrium may exist. For example, it may be seen from figure 1 that although the potential at the surface c of a dry particle is lower than at any point within the liquid at a or b except at the solid-liquid boundary, the movement from a to b or b to c except by evaporation and recondensation may involve an actual increase in potential energy. Under ordinary circumstances, however, there is no doubt a continuous channel of a meandering character through which the principal movement may take place without distillation. Neglecting the influence of gravity, the gross

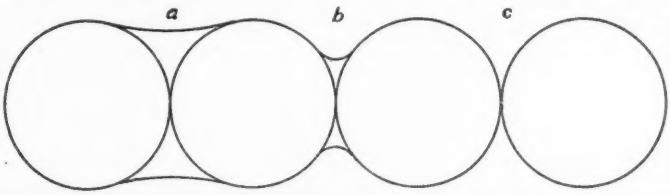


FIG. 1. DIAGRAMMATIC SKETCH OF SOIL-WATER CONFIGURATION IN TWO DIMENSIONS IN AN IDEAL CASE OF UNIFORM SPHERICAL PARTICLES ARRANGED IN LINEAR SEQUENCE

energy of such a system is composed of three types of surface energy, viz., liquid-air, liquid-solid, and solid-air. It should be noted of course that this analysis applies only to a chemically inert system where electrical and chemical energy are in no way concerned. Let these surface energies per unit area be denoted by the symbols, σ_1, σ_2 and σ_3, respectively, and the areas of such surfaces by S_1, S_2 and S_3. The gross surface energy E_σ may then be written.

$$E_\sigma = S_1\sigma_1 + S_2\sigma_2 + S_3\sigma_3 \tag{1}$$

the condition for equilibrium, relative or absolute, being that,

$$\delta E_\sigma = \delta\,(S_1\sigma_1 + S_2\sigma_2 + S_3\sigma_3) = 0 \tag{2}$$

If we take into account gravitational energy and denote by h the height measured from a suitable origin, denoting the gravitational energy per unit mass by gh, the effective moisture density or mass per unit aggregate volume by ρ, the volume by v, the gravitational energy integral by E_g, we may write,

$$E_g = g\int_0^{v_1} \rho h dv \tag{3}$$

If, in addition, a part of the air originally occupying the pore space in the soil becomes entrapped, new surfaces may be developed as a result of bubbles forming, etc., and the energy thus involved must be taken into account by proper construction of equation (1).

The gross energy E of the system may therefore be expressed as follows:

$$E = E_\sigma + Eg = S_1\sigma_1 + S_2\sigma_2 + S_3S_5 + g\int_0^{v_1} \rho h dv \qquad (4)$$

The general case may involve each of the several terms of (4). Beneath a shallow mulch, however, in a field soil, it would seem that $S_3 = 0$, and S_2 remains constant, and the two terms, $S_1\sigma_1 + g\int_0^{v_1} \rho h dv$, alone are concerned as variable factors. In the special case of horizontal flow by capillarity the gravitational term becomes fixed and we are concerned only with $S_1\sigma_1$. When the soil is completely saturated $S_1 = 0$ and we have movement by hydrostatic pressure. The latter case has been treated by Slichter (6) and the problem of horizontal capillary flow has been discussed by the author, as above stated.

In a homogeneous insoluble soil with a porosity and arrangement of particles which does not change with the time, there exists a characteristic capillary constant which, with the moisture content and the moisture gradient, determines the magnitude and direction of the capillary current. For a stratified soil, it is apparent that a "compromise" value of such constant must obtain at the boundary, and, for a soil which varies continuously in texture, such transmission function is no longer independent of position, and a calculation of the capillary current at a given point would involve not only a measurement of the moisture content and moisture gradient, but also a measurement of the transmission function for the point in question.

The following equations are quoted from the article[1] (5, p. 314) above cited, where p is written for the pressure due to curvature and v expresses the velocity of the water:

$$\frac{dp}{dx} = (K_2/\rho^{\frac{1}{3}})\, d\rho/dx$$

$$v = (K_3/\eta)\, \frac{dp}{dx}$$

and if it is remembered that the product of the density ρ and the velocity v is flux per unit area, the following relation may be readily derived:

$$K = f\,\rho^{\frac{1}{3}}/p$$

where f is written for the magnitude of the capillary stream per unit area and p is written for the moisture density gradient or the differential coefficient $d\rho/dx$, x being a coördinate defining the position of the point considered with respect to any convenient origin, the case considered being the flow in one dimension. The factor K involves implicitly the effective radius of the soil particle, the porosity of the soil, and, as a linear factor, the ratio of the

surface tension and the coefficient of viscosity of the water. It has the dimensions $\frac{M^{\frac{1}{2}}L}{T}$. Subject to possible modifications in the original hypotheses this factor may be regarded as a capillary transmission constant.

The direct determination of this constant for a given soil involves the measurement of the moisture density, density gradient, and capillary flow, and we have made preliminary determinations both in the laboratory and in the field by this direct method, although it is laborious.

We have also used a modified method whereby we may obtain the desired information indirectly. A series of curved irrigation sources, convex toward the soil to be irrigated, as illustrated in figure 2, have been provided. These consist of flat galvanized iron pans 1 inch in depth, bounded by two circular and two radial edges as indicated, the water being fed over the top of the "irrigation ditch" by means of an 8-ply linen wick. The water is maintained at a constant level in the ditch and the amount necessary to maintain this level is measured with a burette and recorded with the time. In addition the distance of the water-front as it advances into the soil is recorded. The porosity of the soil is also measured and the density at the source is obtained on the assumption that there is complete saturation. The following calculation will illustrate the method of obtaining the desired information:

If c represents the quantity of water which has moved into the soil from unit area of a vertical section at the source, and if a is the distance the water-front has moved out from the source, and if r is the radius of curvature of the source, then the mean moisture density throughout the wetted area may be expressed as follows:

$$\rho = \frac{\theta cr}{\frac{\theta}{2}(a^2 + 2ar)} = \frac{2cr}{a^2 + 2ar}$$

where θ is the angle of divergence of the circular segment.
The mean density gradient p over this area is

$$p = \frac{\frac{2cr}{a^2 + 2ar} - \rho_0}{\frac{a}{2}} = -\frac{2}{a}\left(\rho_0 - \frac{2cr}{a^2 + 2ar}\right)$$

where ρ_0 represents the moisture density at the irrigation source. The assumption is made that the gradient is constant over the interval a, which is approximately true for small values of a.

A third method involves the measurement of the force moments of the moisture in a series of tubes about an axis through a variable point on the axis of the tube. The distribution of moisture in a soil tube determines the

[1] Attention is called to a factor 2 in equation (2), p. 314, of this article, which should have been omitted; also to the omission of the factor k_2 from equation (7), p. 315.

force-moment about any axis but the converse is not true, and in order to determine the moisture distribution, additional information is needed. For any given distribution the force-moment involves the position of the axis of rotation, as well as the limits of integration in the force-moment integral. If we have a series of soil tubes each of which is bent at right angles, as indicated in figure 3, but the distance of the bend b from the moisture source end increasing regularly from tube to tube, it may be shown by elementary analysis which is omitted for lack of space that the following relation holds:

$$\rho_{(n)} = \frac{M_{(n-1)} - 2M_{(n)} + M_{(n+1)}}{AB^2}$$

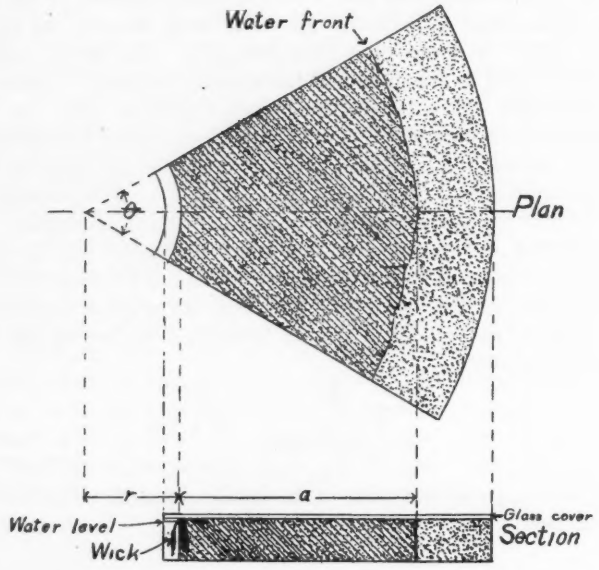


FIG. 2. SKETCH OF SOIL PAN SHOWING RADIAL CHARACTER OF MOISTURE FLOW FROM CIRCULAR SOURCE

where the M's indicate the moments of the moisture beyond the bend about an axis through the point of bending, the subscripts indicating the position of the tube in the series, A the common cross-section of the tubes, B the common difference in the length of branch b from tube to tube of the series, and $\rho_{(n)}$ the average moisture density at the point of bending of the middle one of the series of three tubes involved in the calculation.

A somewhat shorter analysis is given below. If we let x measure the distance of a point from the end at which the moisture enters the tube, a the coördinate of the water front, b the distance to the bend, ρ the moisture

density as previously defined, M the moment, A the cross-sectional area, ρ, x, and b all independent variables, we have,

$$M = A\int_b^a \rho(x-b)dx$$

$$\frac{\partial M}{\partial b} = A\int_b^a \frac{\partial}{\partial b}\Big\{\rho(x-b)\Big\}dx = A\int_b^a(-\dot{\rho})dx$$

$$\frac{\partial^2 M}{\partial b^2} = A\rho_b$$

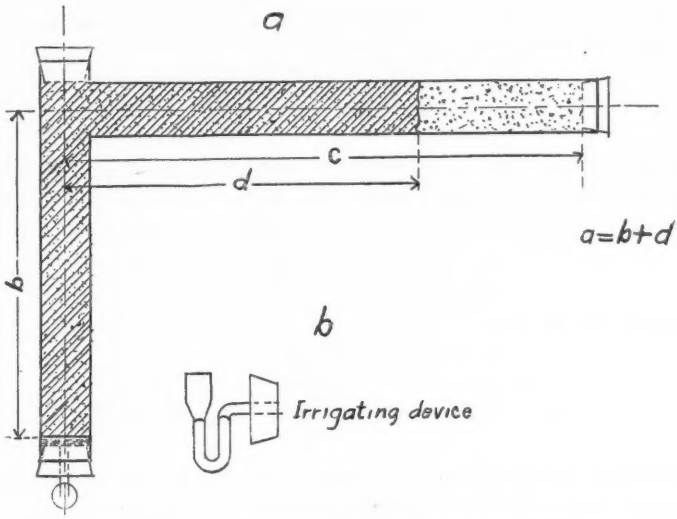


FIG. 3. DIAGRAM SHOWING CONSTRUCTION OF SOIL TUBE

The moment of the moisture in branch c about the axis of branch b is measured for a series of tubes with varying length of the respective branches.

We have had made a series of sectional capillary tubes, each provided with a T, the sections being supplied with a longitudinal window of celluloid. These tubes have been balanced in such a way that the force-moment may be observed from time to time, together with the coördinate of the water front, the respective tubes differing only in the relative lengths of arms b and c (fig. 3) of the tubes. From these data we can determine the relation between M and b as M varies with the time, and then, from equation (1), we may calculate the value of ρ for a series of points along the tubes. A knowledge of ρ as a function of x in which the time enters as a variable paramenter is sufficient for an evaluation of the transmission constant, provided a sufficient range of values of ρ and $\dot{\rho}$ is obtained.

Before discussing the preliminary results reported below, it may be of interest to point to some well known experimental facts bearing on the general validity of assumptions made in the theoretical solution cited above. Experimental data are available from various sources, exhibiting the form of the function involving the quantity of capillary moisture absorbed and the time, also the coördinate of the water front and the time. These functions appear to be of parabolic form and it will be noted that the following development upon theoretical grounds leads to simple parabolae.

Let us consider any point b in a tube of soil carrying capillary moisture. Let Q represent the moisture which has passed beyond this point at any given time t. This may be expressed as the integral of the density ρ between the limits a and O, where a is the coördinate of the water front measured from the point b taken as the origin, thus,

$$Q = \int_0^a \rho dx \qquad \text{(A)}$$

If we may assume that $\rho = (Ax + B)^{\frac{1}{2}}$ (see article cited, p. 315, which purports to be true only for a *steady* state, the integral is readily obtained, giving,

$$Q = \frac{2}{5A}\left[(Ax + B)^{\frac{5}{2}}\right]_0^a \qquad \text{(B)}$$

Expanded, this becomes,

$$Q = \frac{2}{5A}\left[B^{\frac{5}{2}} + \frac{5}{2}B^{\frac{3}{2}}Ax + \frac{\frac{5}{2}\times\frac{3}{2}}{\underline{|2}}B^{\frac{1}{2}}(Ax)^2 + \ldots\right]_0^a \text{(C)}$$

a converging power series in (Ax) which, upon substitution of limits and neglecting terms in $(Ax)^3$ and beyond, becomes,

$$Q = B^{\frac{1}{2}}a\left(B + \frac{3}{4}Aa\right) \qquad \text{(D)}$$

where $$A = \frac{\rho_a^{\frac{1}{2}} - \rho_0^{\frac{1}{2}}}{a} \qquad \text{(a negative quantity)}$$

and $$B = \rho_0^{\frac{1}{2}}$$

the subscripts serving to define the point concerned. Substituting for A and B their values as thus expressed, we obtain

$$Q = a\,\frac{(\rho_0 + 3\rho_0^{\frac{1}{2}}\rho_a^{\frac{1}{2}})}{4} = \int_0^{t_1} f dt \qquad \text{(E)}$$

where f expresses the flow across unit area in unit time.
Writing for brevity

$$c_1 = \frac{\rho_0 + 3\rho_0^{\frac{1}{3}}\rho_a^{\frac{2}{3}}}{4}$$

this becomes,

$$Q = c_1 a = \int_0^{t_1} f dt \tag{1}$$

If c_1 is independent of a, which is true only when ρ_a does not appreciably change with a, we obtain, upon differentiation,

$$da/dt = f/c_1 \tag{2}$$

From equations (4) and (5), p. 314, of the article cited, we have

$$\rho v = f = \left(K \frac{d\rho}{dx}\right) \Big/ \rho^{\frac{1}{3}} \tag{3}$$

where K is the transmission constant previously referred to. Eliminating f from (2) and (3), we obtain,

$$da/dt = (K/c_1) \frac{d\rho}{dx} \Big/ \rho^{\frac{1}{3}} \tag{4}$$

the density and density gradient being the values for the point b. Differentiating the equation,

$$\rho = (Ax + B)^{\frac{3}{2}}$$

we obtain,

$$\frac{d\rho}{dx} = \frac{3A}{2}(Ax + B)^{\frac{1}{2}} = \frac{3}{2} AB^{\frac{1}{2}} \text{ for } x = 0$$

Substituting again for A and B, we have,

$$\frac{d\rho}{dx} = \frac{3}{2} \frac{(\rho_a^{\frac{1}{2}}\rho_0^{\frac{1}{2}} - \rho_0)}{a}$$

Writing for convenience,

$$c_2 = \frac{3}{2}(\rho_a^{\frac{1}{2}}\rho_0^{\frac{1}{2}} - \rho_0)$$

we obtain,

$$\frac{da}{dt} = \left(\frac{Kc_2}{c_1\rho_0^{\frac{1}{3}}}\right)\left(\frac{1}{a}\right)$$

If we write again for brevity,

$$\phi = \frac{c_2}{c_1\rho_0^{\frac{1}{3}}} = \frac{6(\rho_a^{\frac{1}{3}} - \rho_0^{\frac{1}{3}})}{\rho_0 + 3\rho_0^{\frac{1}{3}}\rho_a^{\frac{2}{3}}}$$

we obtain finally

$$a^2 = 2K\phi t \tag{5}$$

Or, again, from (1),

$$a = Q/c_1$$

whence,

$$Q^2 = 2K\phi c_1^2 t$$

or

$$Q^2 = 2K\theta t \tag{6}$$

where

$$\theta = \phi c_1^2 = \frac{3}{8}\rho_0^{\frac{1}{3}}(3\rho_a^{\frac{4}{3}} - 2\rho_0^{\frac{1}{3}}\rho_a^{\frac{1}{3}} - \rho_0^{\frac{4}{3}})$$

It is true of course that ϕ and θ may depend upon a, but, as stated, where ρ_a does not appreciably change with a these functions may be regarded as independent of a.

DISCUSSION OF EXPERIMENTAL RESULTS

A considerable amount of experimental data have been obtained from our laboratory work, and in addition some work has been done in the field at the experimental farm at Greenville, and the prinicpal results have been summarized in the following pages.

In figure 4A is plotted a series of curves representing the moisture distribution as it changed with the time in a small rectangular box of soil 6 by 9 cm. in cross-sectional area, one end of which was bent downward and kept permanently in contact with free water maintained at a constant height about 10 cm. below the center of the box. Samples were taken with a small cork borer at frequent intervals and moisture determinations were made by the usual method of weighing and drying. The data represent the mean of observations taken from duplicate boxes. The vertical lines are drawn at distances corresponding to the position of the water front at various intervals of time and the point of intersection of these lines with the distribution curves of corresponding date should determine the moisture per cent at the water front. From the fact that these values appeared to vary irregularly about a mean as the water front advanced, the mean value was assumed to represent a constant moisture per cent at the water front. In reality this would doubtless diminish slowly with the time. In plot 4B is shown a series of straight lines passing through a common point on the moisture per cent axis representing the moisture per cent at the source. Each curve of the series was determined by this common point and the point of intersection of the horizontal line representing the moisture per cent at the water front with a vertical line marking the position of the water front at the time. The area bounded by each curve of the family, the axes of coördinates, and the vertical line, is proportional to the quantity of moisture in the soil at the time represented by the vertical line, and the difference in this area for successive curves divided by the time interval, represents the mean flow into the soil during the interval. The moisture gradient is proportional to the slope of the mean distribution curve over the interval, and the moisture density is proportional to the ordi-

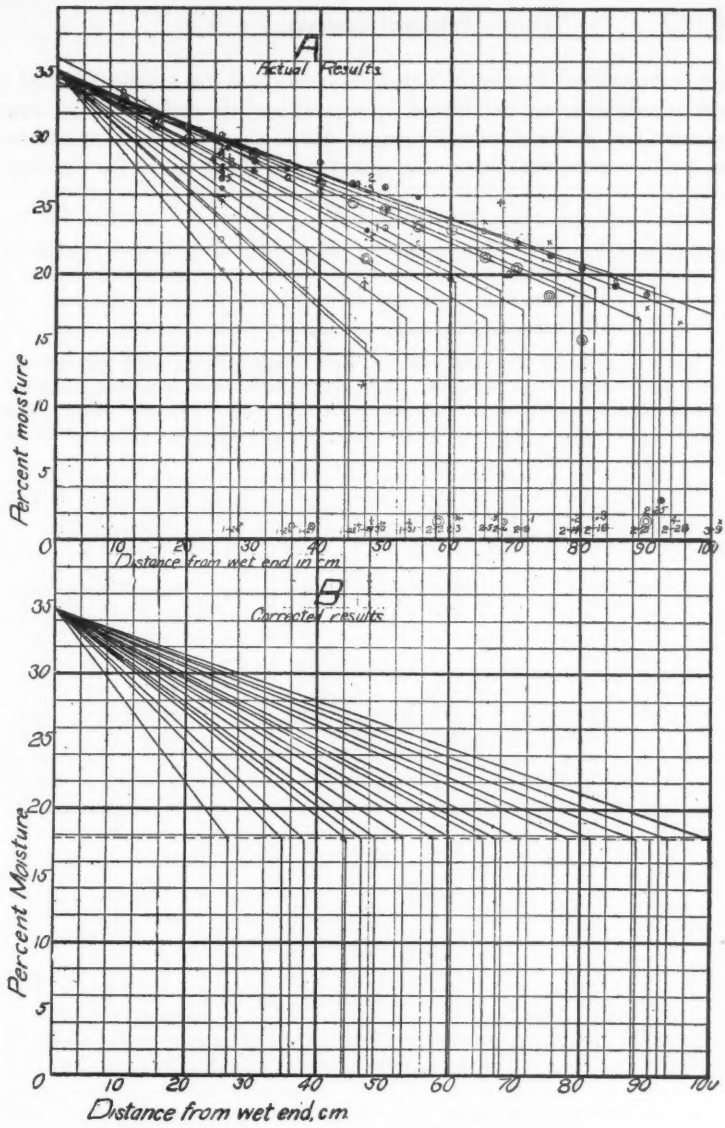


FIG. 4. MOISTURE-DISTRIBUTION CURVES IN LABORATORY TEST

The curves at the top are drawn to illustrate the moisture distribution at successive intervals in a laboratory test of the horizontal capillary flow. Below is shown a series of curves passing through a common point and terminating in a horizontal line representing the average moisture content at the water front. The point of intersection of each line of the series with this horizontal line was determined by a vertical line drawn at a distance corresponding to the position of the water front for a given time. If the moisture distribution were a linear function of the distance these curves would give the history of the moisture in this case.

nate of the curve. It may be noted, however, that the functions ϕ and θ previously defined were determined by the value of the ordinate of the common point and the constant moisture per cent at the water front. Sufficient data are therefore available for the calculation of K by use of the equation,

$$Q^2 = 2K\theta t$$

and in column 1 of table 1 are recorded a series of values of K thus calculated.

TABLE 1

Values of capillary transmission constant for Greenville soil

Columns 1 and 2 represent values obtained from a very loose unpacked soil from data obtained by the direct method; columns 3, 4, 5 and 6, from the same soil packed dry by systematic shaking, data obtained from the second method; column 7 the direct method from a field plot; columns 8, 9, 10 and 11, from the same soil well packed by wetting and drying, from the second method*

1	2	3	4	5	6	7	8	9	10	11
1.3	2.5	11.9	7.4	7.8	7.6	6.3	1.4	10.7	2.8	2.9
1.6	2.0	13.3	8.7	7.9	8.0	5.9	1.3	8.7	2.6	2.8
1.6	2.0	14.8	9.4	7.9	8.1	10.2	2.1	6.7	2.5	2.6
1.9	1.9	15.8	9.7	7.7	8.5	13.0	3.2	5.8	2.4	2.6
1.8	1.8	17.4	10.5	7.6	8.0		3.7	7.1	2.4	2.7
1.8	1.7	16.6	10.7	7.3	8.3		4.1	9.6	2.6	3.5
1.9	1.5	17.0	11.4	6.8	7.2		4.7	12.4	3.5	4.3
1.9	1.2	14.4	12.1	7.3	8.2			12.3	3.8	5.1
1.9		18.0	15.0	8.0	8.1			14.0	5.7	4.9
1.9		15.4	13.0	9.1	9.0				6.6	4.3
1.9			13.1	7.7	9.3				7.1	4.6
1.8			13.2	9.4	10.3				9.4	5.4
1.8			13.7	8.8	11.2					6.5
1.5			14.3	8.8	10.7					
1.7										
1.6										
1.6										
1.4										
1.7	1.8	15.5	11.6	8.0	8.8	8.7	2.9	9.7	4.8	4.1

* It should be noted that columns 3, 4, 5, 6, 8, 9, 10 and 11 involved the measurement of the depth of a column of soil of approximately one inch in depth and the precision of this measurement was not entirely satisfactory. Differences, therefore, from column to column may involve considerable experimental error, whereas the variation in each individual column is not dependent upon this measurement.

In order to convert moisture percentages as plotted to moisture densities in c. g. s. units, an apparent specific gravity of the soil of 1.35 gm. per cubic centimeter was used, the value of θ being -0.118 in c. g. s. units. The values given in the table should be multiplied by $-10.^{-3}$ to convert them into c. g. s. units.

In column 2 of table 1 is shown a series of values ranging from 2.5 to 1.2, calculated from the formula,

$$a^2 = 2K\phi t$$

where a is the distance in centimeters of the water front from the wet end of the soil column, t is the time in seconds measured from the beginning of the experiment, and $\phi = -1.0$ in c. g. s. units.

In figure 5 is shown a series of curves representing the moisture distribution in a field plot, the soil being the same as that used in the laboratory. This plot was kept saturated at the surface by continuous sprinkling, and moisture determinations were made during and after the sprinkling at frequent intervals for several weeks. The data obtained from July 31 to August 11 are shown on the plot. The sprinkling was discontinued at the latter date. The curve at the bottom, which is nearly horizontal, represents the moisture condition when the experiment was begun and the other curves represent the condition on July 31, August 2, August 4, August 7, and August 11, respectively. The area bounded by the moisture per cent axis, the original distribution curve, and any curve of the series is proportional to the quantity of moisture which had moved into the soil since the beginning of the experiment. From the equation

$$K = \frac{f\rho^{\frac{1}{3}}}{p}$$

values of K were obtained from the data of figure 5 ranging from 6.3 to 13.0, as recorded in the seventh column of table 1.

Data obtained from the second method are plotted in figures 6A and 6B. As indicated elsewhere in this article, the gradient and the moisture density may involve the radius of curvature of the irrigation source and a wider range of values was obtained by using several pans differing in this respect. Pan no. 1 had a radius of 2.54 cm., no. 2, 7.62 cm., no. 3, 15.24 cm., no. 4, 30.48 cm., no. 5, 60.96 cm., no. 6. 121.92 cm., and no. 7 had no curvature. Two curves have been plotted for each pan, the one representing the total quantity fed into the soil per unit area of the irrigation source, and the time, the other the distance of the water front from the source and the time. Values obtained from the plot, together with a value for ρ_0 of 0.48 as determined on the assumption that the 48 per cent of pore space was entirely full at the source, were substituted in the equation

$$K = \frac{f\rho_0^{\frac{1}{3}}}{p}$$

and in columns 8, 9, 10 and 11 of table 1 are recorded the values obtained from the data in figure 6A. The soil was well packed in this case by a previous thorough wetting and drying. A slight leak through two of the pans, no. 4 and no. 5, and an accident with no. 3, made the data for these cases uncertain and no attempt was made to use them.

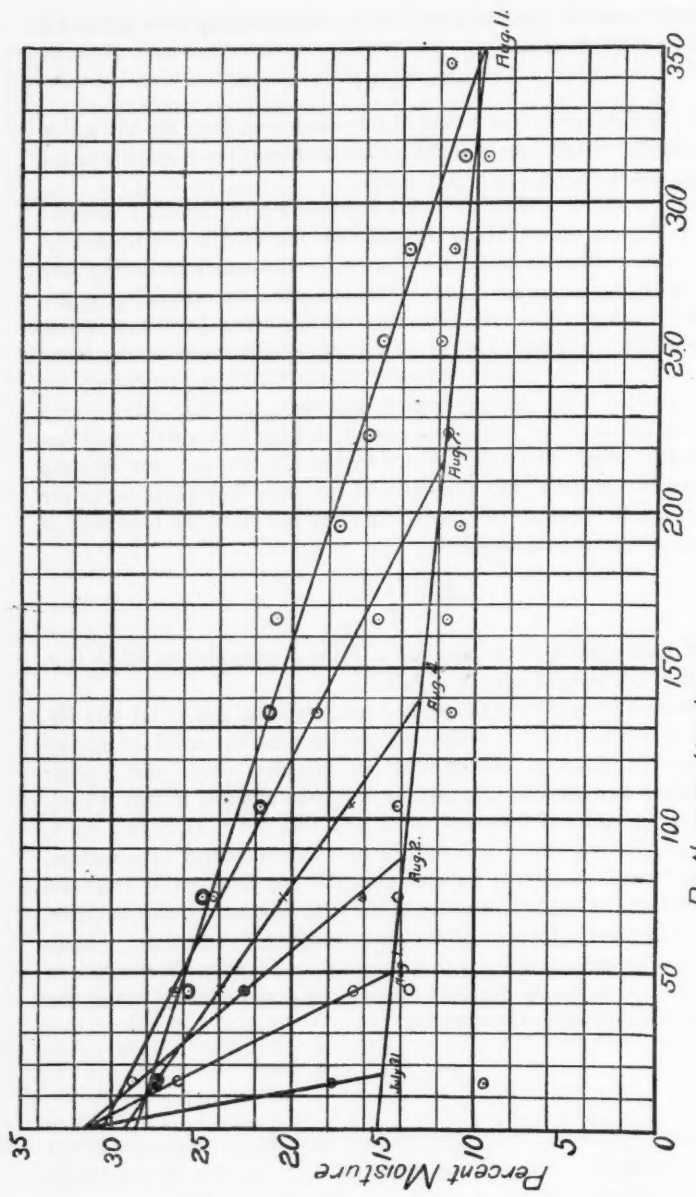


FIG. 5. MOISTURE-DISTRIBUTION CURVES IN FIELD PLOT TEST

The curves in this plot represent the moisture distribution measured at frequent intervals in a field plot where the surface was kept constantly saturated by use of a sprinkler.

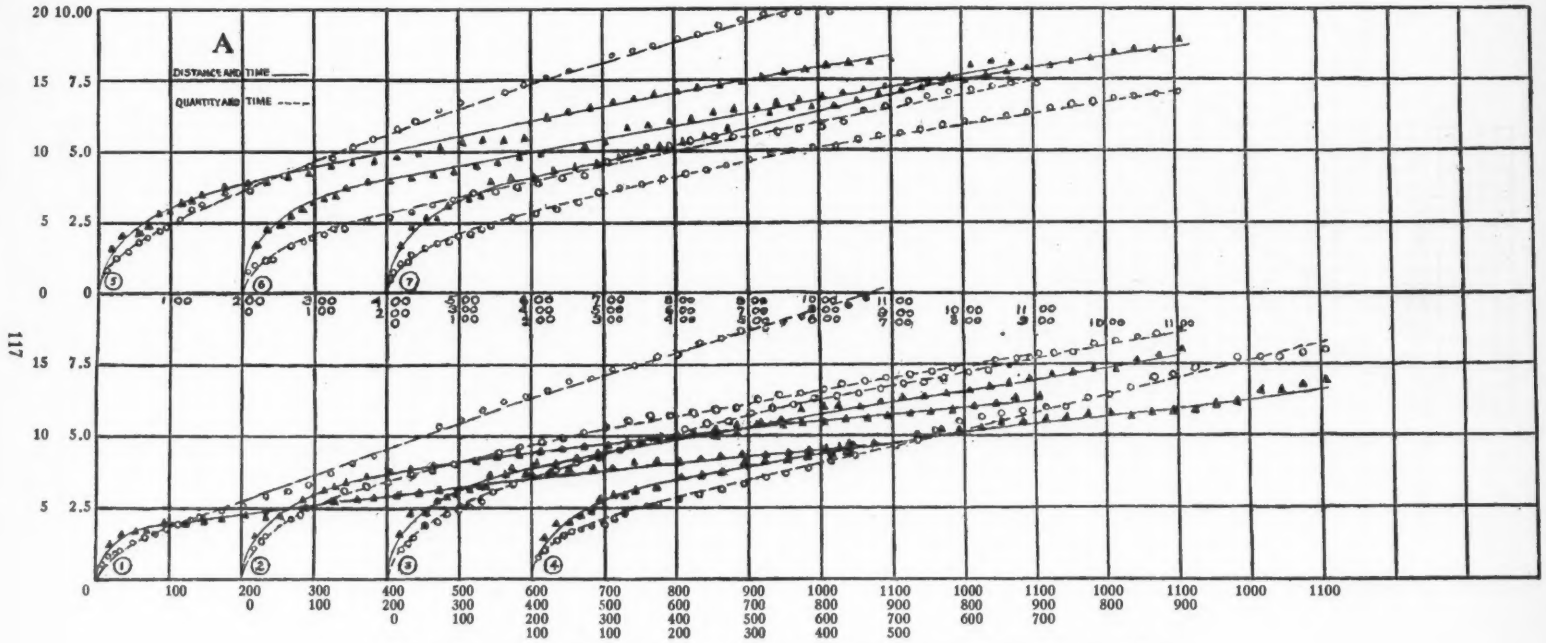
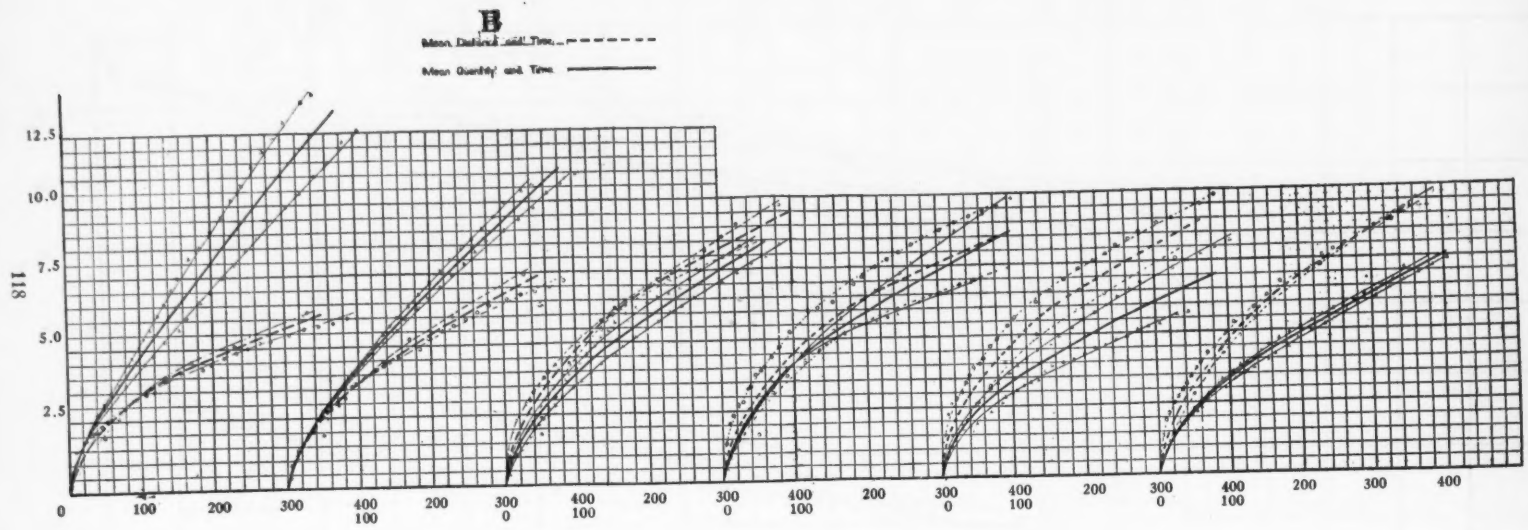


FIG. 6. CURVES ILLUSTRATING THE MOVEMENT OF MOISTURE INTO A RADIAL SECTOR OF SOIL

Two sets of curves are drawn, the one indicating the quantity of moisture which has moved across the unit area of the circular source as a function of the time, the other the distance of the water front from the source as a function of the time.


B
Mean Quantity and Time
12.5
10.0
7.5
5.0
2.5
118
0
100
200
300
400
100
200
300
0
400
100
200
300
0
400
100
200
300
0
400
100
200
300
400

In figure 6B similar results are shown for duplicate trials with the first six pans of the series. The soil in this case was packed without wetting by systematic shaking. The heavy lines represent the mean of two observations, the separate observations being shown on the plot with lighter curves. In columns 3, 4, 5 and 6 of table 1 are recorded values of K calculated from

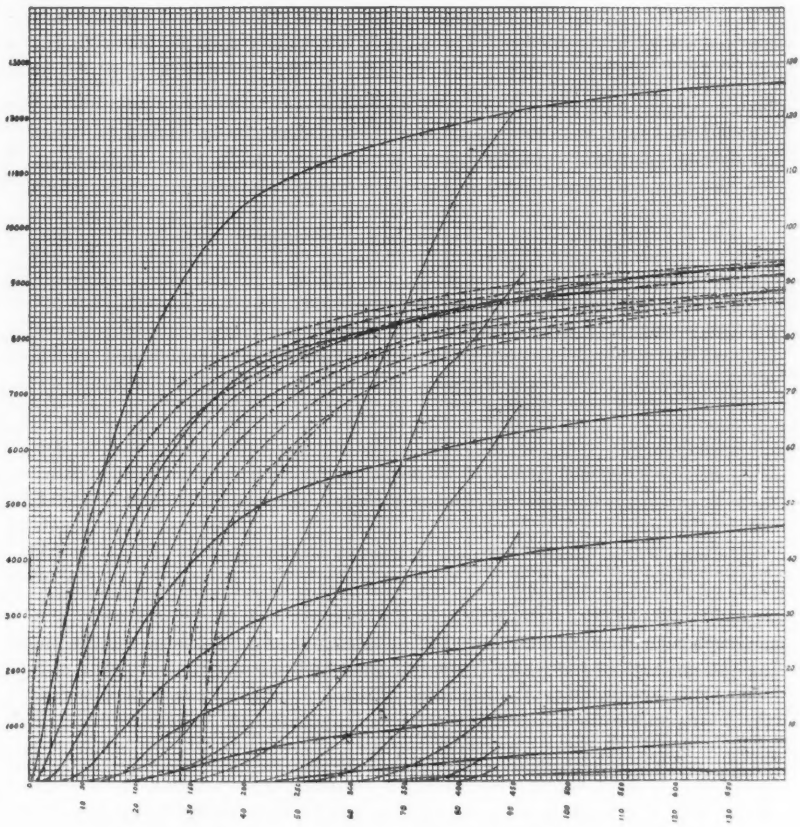


FIG. 7. A PLOT OF DATA OBTAINED FROM A SERIES OF CAPILLARY TUBES

The solid lines represent moment-time data; the broken line, distance of water front from source and time; the light solid lines are the moments plotted against the water front distance.

the data of this plot from pans 1, 2, 5 and 6. Trouble was experienced again with pans 3 and 4 and calculations were not made for these.

In figure 7 are plotted three types of curves representing the data obtained from the third method. A series of nine brass capillary tubes of approximately 5 cm. internal diameter was used. The first was bent at a point 10 cm. from

the end, the second 20 cm., the third 30 cm., and so on. These were balanced in such a way that the moment about an axis through the "source" branch of the tube could be measured with a precision of 1 to 5 centimeter-grams. The series of heavy solid lines are moment-time curves, the broken lines representing the distance of the water front from the wet end and the time; and the light solid lines are the moments plotted against the water front distance. The ordinate represents centimeter-grams with the moment curves and centimeters with the others. The abscissa represents time in hours in two cases and distance in centimeters in the other. The origin is the same for all except the distance-time curves, each of which was shifted horizontally 20 hours from the next preceding curve. These latter curves should of course be strictly parallel except for unavoidable differences in the various tubes. The data for the curves representing the moments plotted against the water-front distances were taken from the other curves rather than from the original tabulated results since these curves eliminate the small oscillations and experimental errors. It will be noted that the ordinates of the points of intersection of a vertical line with the various moment-distance curves represent the simultaneous moments of the moisture in the various tubes. As previously shown, the mean moisture density over the interval between alternate bends may be obtained by adding the simultaneous moments for such alternate tubes and subtracting from the sum twice the moment of the intermediate tube and dividing the result by the product of the cross-sectional area of the tubes (17.7 sq. cm.^{2}) and the square of the bend increment (i.e., the common difference in length from irrigation source to bend between successive tubes—10 cm. in this case).

In figure 8A is plotted a series of curves representing the history of the moisture in the several tubes, the data for which were obtained from figure 7 as above explained. The points at the end of each of the several curves enclosed with large circles mark the intersections of vertical lines representing the position of the water front and straight lines passing through a common point representing the moisture density at the wet end of the tube. These straight lines were drawn to best represent the somewhat irregular moisture densities along the tube. The extrapolated points are taken as indicating approximately the moisture content at the water front. The heavy solid line is drawn to indicate the condition at the water front, and in figure 8B this same line has been drawn and the points of intersection of this line with the vertical lines marking the position of the water front at various times, together with the moisture content at the wet end of the tubes, have been taken to determine a series of approximately straight lines purporting to represent more nearly the actual history of the moisture in the tubes. From this plot the constant ϕ has been determined and from this the transmission constant has been calculated, averaging -4.7×10^{-3} c. g. s. units.

The curves in 8A have been drawn in zig-zag fashion in order more clearly to indicate the actual points determined from the data of figure 7. The wide

irregular variation from point to point may be partly explained by assuming that considerable amounts of air were entrapped at the wet end of the tube at the beginning of the experiment, the effect of which would be made manifest in actual fluctuations in the moisture content. In order to eliminate as much as possible accidental errors due to irregularities in individual tubes, results were calculated for a series of points by a particular combination of tubes and the mean of successive values was then taken to indicate the moisture content at intermediate points, and a consideration of the precision of the experiment indicates that these marked differences cannot be entirely accounted for by experimental error.

Without attempting to give a detailed account of the measure of precision of the experiment, it may be noted that by allowing an error of 0.01 cm. in the length of the lever arms of the levers which were used to balance the tubes, 0.01 gm. in the weights, 0.01 mm. in the diameter of the tubes, and 0.01 cm. in the length of the bend increment of the tubes as previously referred to, the probable error of an individual determination of the density should not exceed 0.1 gm. per cubic centimeter. For actual variations with the time for determinations involving any given combination of tubes the only experimental error involved is the error in the weights used to balance the tubes. The formulae used were those given by Mellor in his "Higher Mathematics for Students of Chemistry and Physics" and the calculations were made on the assumption that each individual determination of the density involved the sum of three independent terms. An increase in the actual number of tubes used in the series would materially increase the reliability of results obtained.

The tubes were irrigated with measured quantities of water, all receiving the same amount. Small glass tubes, bent as illustrated in figure 3B, were used for irrigating the soil, the aim being to maintain the moisture in the bend at such a constant height as to avoid hydrostatic pressure and at the same time provide available free water for the end of the soil column. The rate of application of water proved somewhat arbitrary, however, since it was difficult to maintain a definite height in any of the various tubes. It can not be said, therefore, that the curves of figure 7 representing the position of the water front at different times are exactly as they should have been had the wet end of the tubes been maintained constant by some other device. From the mean of these curves, however, calculations of the constant were made by means of the formula,

$$a^2 = 2K\phi t$$

the mean value of the constant ϕ (-1.4) being determined as previously shown from the data of figure 8B. In table 2 is given a series of values of K thus obtained. It will be noted that there is a decrease from top to bottom of the various columns. This may be partly accounted for from the fact that this formula was derived by neglecting terms in a converging series involving

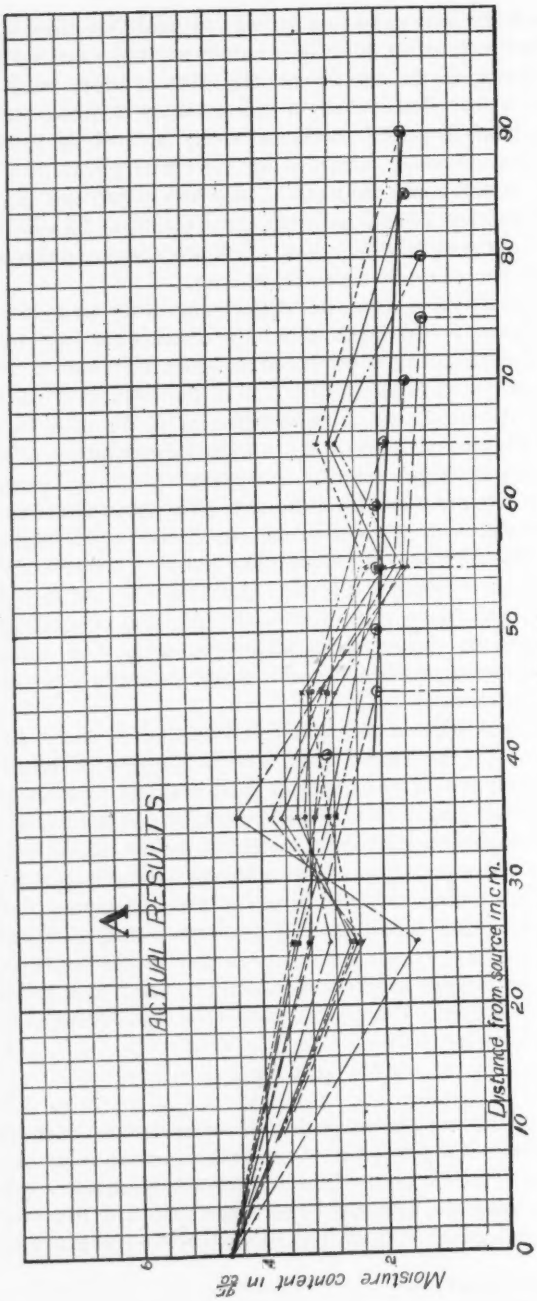

A
ACTUAL RESULTS
Distance from source in c.m.
Moisture content in %
0
10
20
30
40
50
60
70
80
90

FIG. 8A

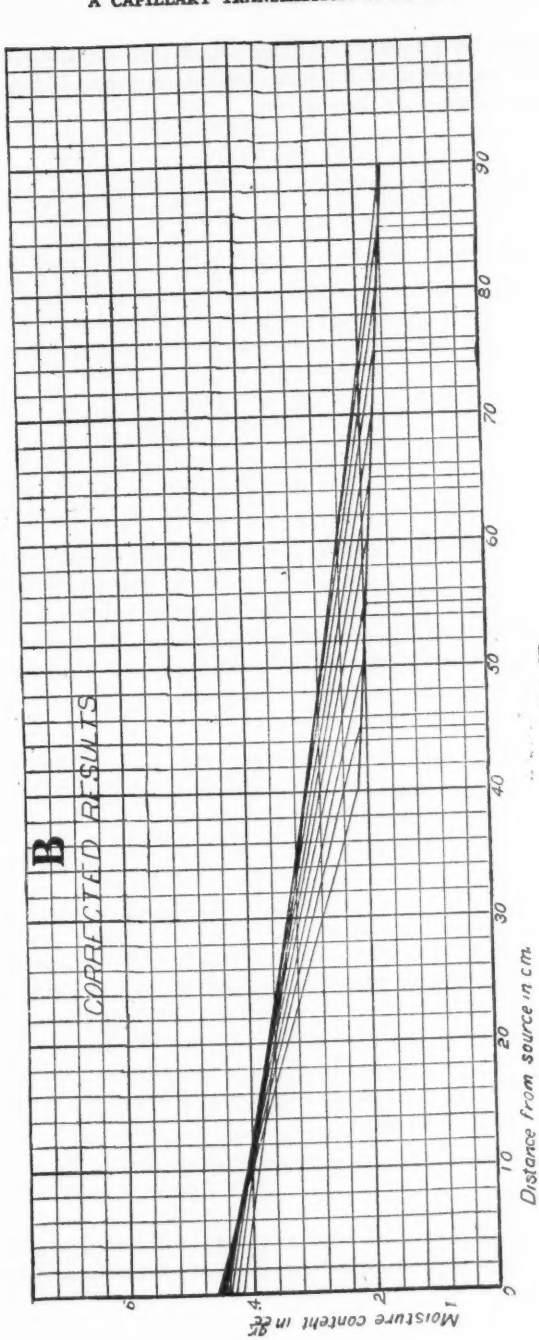

B
CORRECTED RESULTS
Moisture content in cc.
0
2
4
6
Distance from source in cm.
10
20
30
40
50
60
70
80
90

FIG. 8B

quantities which become increasingly important with increase of the time t. It is probable, however, that the somewhat arbitrary rate of irrigation may have had some influence on these figures.

TABLE 2

Values of capillary transmission constant for Greenville soil obtained from laboratory data by means of formula, $K = \frac{a^2}{2\phi t}$

1	2	3	4	5	6	7	8	9	MEAN
5.8	5.8	6.3	5.5	5.4	6.2	5.6	5.4	5.5	
6.3	6.5	5.0	4.8	5.1	6.1	5.7	5.2	4.9	
5.2	6.6	4.7	4.7	4.9	5.4	5.1	4.8	4.7	
4.7	5.1	4.5	4.5	4.4	4.5	4.5	4.2	4.3	
4.2	4.7	4.0	4.0	4.0	4.4	3.6	3.4	3.8	
3.7	3.5	3.4	3.4	3.2	3.1	3.0	2.9		
5.0	5.2	4.6	4.4	4.5	5.0	4.6	4.3	4.6	4.7

The values obtained for this transmission function as recorded in the tables were obtained with the same soil but there were in reality four conditions of porosity involved, viz., an extremely loose unpacked soil, a soil well packed by previous wetting and drying, a soil packed dry by a systematic tapping of the tube without tamping, and a soil in the field, the latter being a case of flow under gravity and capillarity. The means for the several soil conditions are recorded in table 3.

TABLE 3

Mean values of K for Greenville soil

UNPACKED	PACKED DRY	FIELD SOIL	SOIL WELL PACKED	MEAN
-1.8×10^{-3}	-7.4×10^{-3}	-8.7×10^{-3}	-5.4×10^{-3}	-5.8×10^{-3}

The following illustrative calculation has been made on the asumption that -5.8×10^{-3} is the correct value of this constant for Greenville soil under average conditions and on the further assumption that the influence of gravity may be neglected, which should in reality be taken into account.

Problem. From a water-table 12 feet below the suface in a soil such as the Greenville soil, calculate the amount of water available at the surface.

Solution. From the formula,

$$f = \frac{-5.8\, p \times 10^{-3}}{\rho^{\frac{1}{2}}}$$

we may obtain the flow in cubic centimeters per square centimeter of surface per second of time. Let us assume the amount of moisture in grams per

cubic centimeter at the point of saturation ρ_0 to be 0.48, and the mean value of ρ 0.24. The gradient p is then obtained in c. g. s. units as follows:

$$p = \frac{0.0 - 0.48}{12 \times 30.5} = -1.31 \times 10^{-3}$$

The cube root of the mean density is 0.62. We therefore obtain

$$f = \frac{(-5.8)(-1.31)}{0.62} \times 10^{-6} = 1.2 \times 10^{-5} \text{ cc. per second.}$$

By an obvious reduction it may be seen that this would be sufficient water to cover the surface to a depth of approximately 12 inches in a period of thirty days.

It is true, of course, that caution should be exercised in the use of this constant until further experimental work has been done. It would seem, however, that there is more or less merit in the method of attack of the problem and it is hoped that other workers may become interested in this point of view. For soils high in colloidal material it may be urged that this transmission function is dependent upon the moisture content, but it does not appear that an average soil should vary appreciably under field conditions because of expansions or contractions of colloidal particles. In any event a fair solution of the problem for the ideal case should lend some assistance toward the solution of those cases which are more complex.

SUMMARY

1. A capillary transmission constant has been defined on theoretical, grounds. This constant is similar to the specific electrical conductivity of metals and to the specific thermal conductivity of heat conductors.

2. Methods have been described for the measurement of this constant in the laboratory.

3. Preliminary results have been obtained from the various methods for the Greenville soil, including values for soil under field conditions, the latter not corrected for the influence of gravity. The values obtained for this soil under various conditions of porosity range from -1.8×10^{-3} for a very loose unpacked soil to -8.7×10^{-3} for a field plot, with a mean value of -5.8×10^{-3} c. g. s. units.

4. An illustrative calculation has been made indicating that approximately 12 inches of water may be available from a 12-foot water-table in a period of 30 days. This figure has not been corrected for the influence of gravity.

5. Emphasis is laid on the general method of attack rather than upon the finality of results obtained.

In conclusion, acknowledgment should be made to Mr. N. E. Edlefsen and Mr. S. K. Ewing for assistance in the laboratory and for valuable suggestions

that have been made from time to time, and to Dr. F. L. West, the head of the department, for coöperative encouragement during the progress of the work.

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ORGANIC PHOSPHORUS CONTENT OF OHIO SOILS

C. J. SCHOLLENBERGER

Ohio Agricultural Experiment Station

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INTRODUCTORY

Considering the nature of the changes which are brought about in soil constituents through biochemical agencies, it has been the opinion of various soil investigators that an appreciable part of the soil's total supply of phosphorus is in organic combinations.

The methods used in the earlier work on this subject gave indications of a qualitative nature only, and did not approach with any degree of exactness to an accurate measure of the organic phosphorus of the soil. In fact, until recently the evidence that a significant part of the soil's supply of phosphorus is organically combined was largely circumstantial. It was assumed that the presence of an excess of phosphorus in the surface soil accompanied by an excess of organic carbon and nitrogen, while potassium and other inorganic constituents were about the same as in the subsurface, was conclusive evidence of the presence of organic phosphorus. Other methods of estimation, such as increased solubility of phosphorus in dilute acids after ignition or treatment with oxidizing agents, have been proposed, but the indictions of some of these have been called into question, while others have perhaps never received the extended study their possibilities would warrant.

Previous to the work of Potter and Benton (4), who developed what is apparently a reliable procedure for the determination of the organic phosphorus in ammonia extracts of soil, there has been no method for the estimation of any part of the organically combined phosphorus in soil which could be considered in any degree satisfactory. In a former paper (7) from this laboratory, attention has been directed to defective features in some of these earlier methods and data published which were obtained in an extended study of the method described by the authors named. The procedure necessary for securing the maximum possible extraction of organic phosphorus from the soil studied was described in the paper cited. The data there reported led to the conclusion that the organic phosphorus obtained in ammoniacal extracts of the acid-extracted soil is a very close approximation to the soil's entire content of phosphorus so combined.

As a part of a comprehensive plan for the study of the phosphorus combinations in soils, and for the purpose of obtaining further information on the

general subject of organic phosphorus in soils, it has been considered desirable to compare virgin and cultivated surface and subsurface samples from a number of representative types of Ohio soils, with respect to organic phosphorus content and such other data as may appear to be related thereto. The work done in pursuance of this plan forms the subject matter of the present paper.

SOILS STUDIED

The samples considered here are from two depths, 0–7 inches and 7–15 inches, designated "a" and "b" respectively, in the laboratory numbers. They have been selected from a number of samples taken from important soil types of the state. The points considered in their selection have included similarity in total potassium content, as indicating similarity in mineralogical composition, between the virgin and cultivated samples and the surface and subsurface. In addition, samples showing any abnormal departure from the average of the type or inconsistencies in total phosphorus or nitrogen content have not been included. Another point to which much importance was attached is similarity in reaction to litmus paper, although several exceptions to this have been admitted if otherwise suitable. The reaction of these soils, as well as the calcium, magnesium and carbonate content have been discussed at length in a former publication (1). The names applied to the soil types represented by these samples are those of the Ohio soil survey.

The history of none of the cultivated samples is known with exactitude. Sample 36 was stated by the owner to have been cultivated not less than 70 years. Numbers 19 (from a dairy farm) and 34 had been cropped for 50 years, 21 and 38 "a long time," and 32 for 30 years. It is believed that none of the cultivated soils has been under the plow for less than a generation, and so far as could be learned none had ever been limed or had received any commercial fertilizer. The virgin samples were all taken from land, usually woodland with large trees, which was known with reasonable certainty never to have been cropped. In selecting locations for samples, care was taken to secure the virgin samples in as close proximity as possible to the place where the cultivated samples were obtained and from land of similar topography, in each case typical of the soil area being sampled.

ANALYTICAL METHODS

The methods of analysis employed were essentially those described in a former paper (7). The extractions with acid and dilute ammonia were conducted as follows. Three hundred grams of ground soil were weighed into a liter Florence flask and the flask filled with approximately 1 per cent hydrochloric acid (25 cc. concentrated acid per liter), stoppered and shaken frequently for 1 hour. The contents of the flask were then shaken up and poured upon a 15-cm. Büchner funnel with two filter paper circles upon the plate.

As soon as filtered, the soil was washed with 2 liters of the 1 per cent hydrochloric acid and finally with 1 liter of saturated carbon dioxide solution, which was found sufficient to remove the hydrochloric acid in every case. Suction was employed in the filtration but care was taken not to allow the wash liquids to be drawn through too rapidly in case a very permeable sample was being filtered. The filtrates were made to 4 liters, by weight, mixed and 300-cc. aliquots taken for the determination of phosphorus removed from the soil by washing with 1 per cent hydrochloric acid. The cake of soil was transferred to a Winchester bottle, the rinsings from the funnel, etc. added, and the requisite amount of strong ammonia to make the finished solution 2.5 per cent NH_3 (150 cc.). The bottle was finally made to such weight with water that the volume of the 2.5 per cent ammonia in contact with 300 gm. of soil was 1500 cc. The two filters partially compensate for the loss in weight from acid extraction, and as none of these soils contained an undue amount of acid-soluble material, this and the slight evaporation during filtration were considered sufficient compensation. After shaking for 6 hours in a mechanical shaker 3 gm. of powdered ammonium carbonate were added and the mixtures shaken and allowed to stand some time. The contents of the bottles were finally shaken and poured into 25-cm. Büchners with two paper circles, connected by large rubber stoppers to 4-liter wide-mouth bottles. The funnels were covered with well fitting glass plates and after several hundred cubic centimeters had run through and the filtrates were free from clay, the apparatus was disconnected, the filtrates poured back and the apparatus again connected. The bottles were partially exhausted (a 25-cm. mercury vacuum was found safe) sealed and allowed to stand until the extract had passed the filter, renewing the vacuum from time to time if necessary. A very small amount of glycerine was found indispensable as a lubricant for the rubber stoppers.

The method for inorganic phosphorus in ammonia extracts has been very satisfactory with all these samples with the excepion of those representing the Brookston silty clay loam (36 and 37). In these cases all the precipitates were abnormal in appearance and behavior, and only by redissolving the ignited magnesium pyrophosphate and reprecipitating with official molybdate solution and magnesia mixture could the results of two determinations be made to agree. As the extracts of these samples gave no unusual difficulty in the total phosphorus determination, it is probable that the contaminant was partly organic. In the determination of total phosphorus in ammonia extracts by the wet combustion method, it was found that the final precipitates of magnesium ammonium phosphate from some of these samples were contaminated with iron, therefore it was necessary to resort to reprecipitation by molybdate and magnesia mixture. Although not absolutely necessary in all cases, this was always done in the work here reported.

The phosphorus in the soil was determined by the magnesium nitrate-volumetric method (2). Total nitrogen was determined by the official method (2). Ammonia-soluble organic matter (humus) and humus ash were deter-

mined by evaporating 50 cc. of the ammonia extract to dryness in a weighed platinum dish on the steam bath, drying 4 hours at 100°C. in vacuo over P_2O_5, weighing, igniting, and again weighing. No correction for combined water in the ash was applied.

Comparative color of the ammonia extracts was determined by diluting 2 cc. to 100 cc. and comparing in a Schreiner colorimeter with an extract similarly treated and arbitrarily given the value 100. It should be noted that the numbers serving as the index for comparative intensity of color vary directly with the intensity of color. Thus, an extract with the number 50 has one-half the color intensity of the standard.

SIGNIFICANCE OF ANALYTICAL DATA CONSIDERED

In table 1, the analytical data for these soils, of interest in the present connection, are presented. These include total phosphorus in the soil, inorganic and organic phosphorus in ammonia extracts and phosphorus removed from the soil by washing with 1 per cent hydrochloric acid and saturated carbon dioxide solution in preparing the samples for extraction with ammonia solution.

While the direct connection between the acid-soluble and the organic phosphorus content of the soil may not be apparent, the amount of phosphorus removed from the soil by leaching with dilute hydrochloric acid is considered to be of some significance in a soil study of this nature, for the reason that it may serve to indicate variations in the state of combination of soil phosphorus or serve as an index to the more readily soluble or presumably more available part of the total phosphorus, as other procedures of extraction with dilute acids have been supposed to do. It should be understood that the hydrochloric-acid leaching removes much more phosphorus from the soil than does a single extraction with fifth-normal nitric acid, which has been used to a considerable extent for this purpose in the past. This is true, not so much because one is a more powerful solvent than the other, but because a process of leaching tends to reduce to a minimum the reabsorption of phosphorus once dissolved. This phase of the subject has been studied at length by Prescott (6).

From data published in a former paper (7), it appeared that in the case of the soil then studied, inorganic phosphorus absorbed by the soil from acid solution was completely recovered as inorganic phosphorus in water washings and a subsequent ammonia extraction. Unfortunately, no work intended to confirm this point for the soils now under consideration has been done, so that in these cases there is no proof that the absorbed phosphorus is completely removed by a subsequent ammonia extraction. The most that can be said is that the phosphorus neither removed by acid leaching nor appearing in the ammonia extract is about the maximum amount which can be considered to be in a form very resistant to solvents, possibly because it is enclosed in mineral particles. If this last statement is true, it seems probable that there

would be evident, in many cases, a certain uniformity among figures so obtained for virgin and cultivated surface and subsurface soils of the same type, of similar origin and mineralogical composition. Such being the case, it would indicate that the figures for organic phosphorus are probably not grossly inaccurate by reason of incomplete extraction at least, since it is improbable that the surface and subsurface samples would contain the same amounts of organic phosphorus not extracted by ammonia. This phase of the subject will be dismissed with the statement that the percentages of insoluble phosphorus, calculated on the soil, do in most cases show a marked similarity. The variation between soil types is large, but several types show nearly as large differences between surface and subsuface of the same sample. As the percentages can readily be calculated from other data in table 1, they are not tabulated.

The total nitrogen contents of these samples are included, because these serve as indicators of the relative amounts of organic matter in the samples. The comparative color, total organic matter (humus) and humus ash in the ammonia extracts are included to establish their relation to the content of organic phosphorus.

DISCUSSION OF ANALYTICAL DATA

In nearly all cases the virgin surface sample contains more total phosphorus than the corresponding cultivated sample. The same is true of the subsurface samples also, although here the average difference is comparatively small.

The ammonia-soluble organic phosphorus of both depths averages higher with virgin samples than with cultivated. In each depth, the average percentage of the total phosphorus which is in the ammonia-soluble organic form is practically the same in the cultivated samples as it is in the virgin samples. One-third the total phosphorus of the average surface sample is organically combined, while in the subsurface samples the average proportion is one-fifth. As it happens, the extremes are in the cases of the two sandy soils, the Dunkirk fine sand having but 18 and 20 per cent of the total phosphorus in the surface depths of the cultivated and virgin samples, respectively, in the organic form, while the Clyde fine sand shows 52 and 50 per cent so combined in the corresponding samples. The lowest proportion of total phosphorus in organic form in the case of a subsurface sample is found in the case of the virgin Wooster silt loam, 6 per cent; the highest is 47 per cent in the virgin Clyde fine sand.

The proportion of the total phosphorus occurring as ammonia-soluble inorganic averages slightly higher in the subsurface than in the surface samples. The average figure is 11 per cent for both virgin and cultivated samples of this depth, but 8 and 9 per cent, respectively, for surface samples. The extremes are 2 per cent in the subsurface of the cultivated Clyde fine sand and the surface of the virgin Crosby silt loam and 20 per cent in the subsurface of the vir-

TABLE 1.

Data on soils investigated

DESCRIPTION		NUMBER	PHOSPHORUS							TOTAL NITROGEN	COMPARATIVE COLOR OF NH_4OH EXTRACTS	NH_4OH-SOLUBLE ORGANIC MATTER (HUMUS)	HUMUS ASH	ORGANIC P IN NH_4OH-SOLUBLE ORGANIC MATTER	REACTION OF SOIL
			Total	NH_4OH-soluble organic	Organic as per cent of total	NH_4OH-soluble inorganic	NH_4OH-soluble inorganic as per cent of total	HCl-washing-soluble	HCl-washing-soluble as per cent of total						
			per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*		*per cent*	*per cent*	*per cent*	
Wooster loam	Cultivated	4a	0.0530	0.0165	31	0.0045	8	0.0062	12	0.14	63	1.430	0.197	1.15	Acid
		4b	0.0361	0.0058	16	0.0013	4	0.0015	4	0.06	18	0.444	0.213	1.30	Acid
	Virgin	5a	0.0923	0.0210	23	0.0110	12	0.0339	37	0.16	89	1.691	0.170	1.24	Acid
		5b	0.0300	0.0038	13	0.0028	9	0.0043	14	0.04	11	0.309	0.168	1.21	Acid
Wooster silt loam	Cultivated	8a	0.0342	0.0108	31	0.0050	15	0.0028	8	0.12	52	1.048	0.169	1.03	Acid
		8b	0.0307	0.0060	20	0.0033	11	0.0011	4	0.07	19	0.551	0.108	1.09	Acid
	Virgin	9a	0.0520	0.0140	27	0.0063	12	0.0072	14	0.16	83	1.454	0.111	0.96	Acid.
		9b	0.0348	0.0020	6	0.0063	18	0.0021	6	0.05	8	0.310	0.090	0.65	Acid
Cincinnati silt loam	Cultivated	19a	0.0613	0.0182	30	0.0056	9	0.0015	2	0.11	67	1.083	0.130	1.69	Acid
		19b	0.0541	0.0038	7	0.0093	17	0.0014	3	0.06	9	0.355	0.069	1.06	Acid
	Virgin	20a	0.0657	0.0202	31	0.0070	11	0.0062	9	0.15	91	1.403	0.171	1.44	Acid
		20b	0.0534	0.0045	8	0.0095	18	0.0045	8	0.06	11	0.384	0.070	1.17	Acid
Clermont silt loam	Cultivated	21a	0.0437	0.0125	29	0.0048	11	0.0010	2	0.10	28	0.870	0.412	1.44	Acid
		21b	0.0288	0.0040	14	0.0023	8	0.0010	3	0.04	5	0.352	0.470	1.14	Acid
	Virgin	22a	0.0464	0.0140	30	0.0040	9	0.0016	3	0.14	40	1.247	0.359	1.12	Acid
		22b	0.0294	0.0045	15	0.0025	9	0.0008	3	0.06	9	0.377	0.484	1.19	Acid

Crosby silt loam	Cultivated	34a	0.0312	0.0120	38	0.0018	6	0.0037	12	0.14	113	1.617	0.106	0.74	Acid
		34b	0.0221	0.0053	24	0.0020	9	0.0017	8	0.06	28	0.576	0.184	0.91	Acid
	Virgin	35a	0.0522	0.0148	28	0.0013	2	0.0042	8	0.17	129	1.920	0.97	0.77	Acid
		35b	0.0242	0.0058	24	0.0008	3	0.0007	3	0.07	34	0.538	0.135	1.07	Acid
Fox silt loam	Cultivated	59a	0.0442	0.0155	35	0.0050	11	0.0024	5	0.11	52	1.091	0.093	1.42	Acid
		59b	0.0472	0.0075	16	0.0063	13	0.0031	7	0.07	23	0.522	0.087	1.44	Acid
	Virgin	60a	0.0524	0.0228	43	0.0048	9	0.0032	6	0.18	85	1.676	1.155	1.36	Alkaline
		60b	0.0451	0.0125	28	0.0040	9	0.0026	6	0.11	48	0.909	0.097	1.38	Alkaline
Dunkirk fine sand	Cultivated	25a	0.0337	0.0068	18	0.0040	11	0.0084	22	0.10	63	1.169	0.085	0.58	Neutral
		25b	0.0200	0.0038	19	0.0025	13	0.0035	18	0.05	21	0.475	0.080	0.79	Neutral
	Virgin	26a	0.0318	0.0065	20	0.0020	6	0.0024	8	0.10	66	1.147	0.061	0.57	Acid
		26b	0.0211	0.0025	12	0.0013	6	0.0011	5	0.04	11	0.371	0.056	0.67	Acid
Clyde (Maumee) fine sand	Cultivated	28a	0.0305	0.0160	52	0.0020	7	0.0053	17	0.16	250	2.356	0.345	0.68	Acid
		28b	0.0284	0.0088	31	0.0007	2	0.0025	9	0.06	68	0.820	0.303	1.07	Acid
	Virgin	29a	0.0561	0.0283	50	0.0032	6	0.0071	13	0.19	185	2.127	0.684	1.33	Acid
		29b	0.0353	0.0165	47	0.0023	7	0.0048	14	0.08	70	0.929	0.244	1.78	Acid
Miami silty clay loam	Cultivated	32a	0.0265	0.0095	36	0.0033	12	0.0020	8	0.12	54	1.136	1.195	0.84	Alkaline
		32b	0.0259	0.0043	17	0.0040	15	0.0017	7	0.08	14	0.475	0.129	0.90	Acid
	Virgin	33a	0.0372	0.0138	37	0.0045	12	0.0060	16	0.18	122	2.097	0.285	0.66	Alkaline
		33b	0.0317	0.0063	20	0.0043	14	0.0021	7	0.08	24	0.614	0.129	1.02	Alkaline

TABLE 1—*Continued*

DESCRIPTION		NUMBER	PHOSPHORUS							TOTAL NITROGEN	COMPARATIVE COLOR OF NH_4OH EXTRACTS	NH_4OH-SOLUBLE ORGANIC MATTER (HUMUS)	HUMUS ASH	ORGANIC P IN NH_4OH-SOLUBLE ORGANIC MATTER	REACTION OF SOIL
			Total	NH_4OH-soluble organic	Organic as per cent of total	NH_4OH-soluble inorganic	NH_4OH-soluble inorganic as per cent of total	HCl-washings-soluble	HCl-washings-soluble as per cent of total						
			per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*		*per cent*	*per cent*	*per cent*	
Lucas silt loam	Cultivated	38a	0.0448	0.0125	28	0.0030	7	0.0010	2	0.13	80	1.161	0.134	1.08	Alkaline
		38b	0.0331	0.0050	15	0.0058	18	0.0007	2	0.06	19	0.455	0.293	1.10	Alkaline
	Virgin	39a	0.0437	0.0118	27	0.0050	11	0.0054	12	0.14	82	1.226	0.202	0.96	Alkaline
		39b	0.0407	0.0080	20	0.0080	20	0.0058	14	0.08	51	0.756	0.326	1.06	Alkaline
Brookston silty clay loam	Cultivated	36a	0.0612	0.0270	44	0.0045	7	0.0061	10	0.20	165	2.224	0.170	1.21	Alkaline
		36b	0.0505	0.0188	37	0.0053	11	0.0038	8	0.12	77	1.103	0.180	1.70	Alkaline
	Virgin	37a	0.1145	0.0535	47	0.0050	4	0.0261	23	0.39	215	3.833	0.211	1.39	Alkaline
		37b	0.0698	0.0235	34	0.0050	7	0.0229	33	0.23	96	1.208	0.139	1.94	Alkaline
Newton loam	Cultivated	49a	0.0509	0.0198	39	0.0033	6	0.0191	37	0.24	214	2.678	0.513	0.74	Alkaline
		49b	0.0368	0.0068	18	0.0033	9	0.0174	47	0.10	67	0.880	0.625	0.77	Alkaline
	Virgin	50a	0.0604	0.0258	43	0.0023	4	0.0220	36	0.28	231	3.351	0.295	0.77	Alkaline
		50b	0.0421	0.0100	24	0.0028	7	0.0209	50	0.10	59	1.000	0.597	1.00	Alkaline
Average of 12 soil types	Cultivated	0–7	0.0433	0.0148	34	0.0039	9	0.0050	11	0.14	100	1.489	0.212	1.05	
		7–15	0.0345	0.0067	20	0.0038	11	0.0033	10	0.07	31	0.584	0.228	1.11	
	Virgin	0–7	0.0587	0.0205	34	0.0047	8	0.0104	15	0.19	118	1.931	0.233	1.05	
		7–15	0.0381	0.0083	21	0.0041	11	0.0061	14	0.08	36	0.642	0.211	1.18	

gin Lucas silt loam. It should be noted that the figure for ammonia-soluble inorganic phosphorus is to some extent influenced by the technique of the previous acid extraction, so that these data are of uncertain significance.

The percentages of the total phosphorus removable by leaching with 1 per cent hydrochloric acid and washing with a saturated solution of carbon dioxide are on the average distinctly higher in the cases of both depths of virgin samples. This is in harmony with the results obtained for fifth-normal-nitric-acid-soluble phosphorus and is doubtless to be attributed to depletion of the more soluble forms of phosphorus as the result of cultivation. In the cases of several types, however, the cultivated sample contains the greater amount of acid-soluble phosphorus.

As might be expected, the data for total nitrogen show very distinctly the effect of cultivation upon the surface soil. The effect upon the subsurface is much less, in fact several samples show as much total nitrogen in the lower depth of a cultivated sample as in the virgin sample of the same depth, or still more. In general, within each type there is apparent a marked relation between total nitrogen and the ammonia-soluble organic matter, organic phosphorus and color. The Clyde fine sand is rather exceptional in the lack of such correlation. In comparing different types a similar, though commonly less exact relation between these constituents is observed. From the averaged data for all types, it was found that the ratio is such that if the ammonia-soluble organic matter of the surface soil is represented by 100, the total nitrogen will approximate to 10 and the organic phosphorus 1. For the subsurface samples, the ratio of soil nitrogen to organic phosphorus is slightly higher, and the relative amount of ammonia-soluble organic matter is somewhat less.

The percentage relations of the ammonia-soluble organic phosphorus to humus are included in table 1. From these, it may be observed that the least proportion of organic phosphorus to organic matter in ammonia solution is found in the case of the surface soil of the Dunkirk fine sand; the figure here is slightly less than 0.6 per cent for both samples, and the subsurface samples also show percentages but a trifle greater. The highest percentage of organic phosphorus in ammonia-soluble organic matter is found in the case of the virgin subsurface of the Brookston silty clay loam, the figure being 1.94 per cent. The percentage of organic phosphorus in the ammonia-soluble organic matter is distinctly higher in the case of the subsurface samples and in most cases the organic matter from the subsurface of virgin samples contains more than that from cultivated samples.

The comparative color of ammonia extracts is more nearly directly proportional to the organic matter in the extract than to organic phosphorus or total nitrogen in the soil. Considering the amount of the color due to ferric hydroxide, it could scarcely be expected to show any very close relations to other constituents of the solution.

The percentages of humus ash contained in the ammonia extracts of these soils do not exhibit any close relation to other constituents found in solution.

In general, it may be said that surface soils containing much organic matter soluble in ammonia run higher than the average in humus ash. Subsurface samples, however, sometimes furnish an extract with more ash than that from the corresponding surface soils. The percentage of ash in the ammonia extract is to a large extent dependent upon the effectiveness of the filtration procedure. It was found in a previous investigation (7) that the method of filtration employed for these samples affords an extract practically free from clay. With most samples ferric oxide is the predominant constituent of the ash.

REACTION OF SOIL AND ORGANIC PHOSPHORUS CONTENT

In so far as the data obtained permit any opinion to be formed, reaction of the soil is without influence upon the organic phosphorus. The soils included in this investigation are predominantly acid; there are but four types in which both cultivated and virgin samples are alkaline. Of these four types, the Miami silty clay loam and the Lucas silt loam are upland soils and the Brookston silty clay loam and Newton loam are representative of the dark-colored, often poorly drained neutral or alkaline soils so common in the northwestern quarter of the state, and formerly referred to the Clyde series of soils on account of their high content of organic matter, which is the distinguishing characteristic of the Clyde series. The soils first named are rather below the average of all the types here considered in total nitrogen, ammonia-soluble organic matter and organic phosphorus, while the second pair of soils are distinctly above the average in all these constituents.

The averaged percentages of organic phosphorus in ammonia-soluble organic matter of these soils are not markedly different from those of the other types considered, nor are the ratios of these constituents to total nitrogen dissimilar when averaged for the four types, although including samples which are near extremes in both directions with respect to ratios of nitrogen, humus and organic phosphorus.

It is true that the dark-colored alkaline soils under discussion are higher than the average in total phosphorus, and that an unusually large proportion of this is present in the organic form. But the Clyde fine sand, although lower in total phosphorus, has an even larger proportion of this in the organic state, and this soil is acid. The only relation existing between reaction and organic phosphorus content seems to follow from the fact that the chief factor favoring the accumulation of organic matter (and organic phosphorus with it) is poor drainage, and this also operates toward the conservation of bases, the soil remaining alkaline if it was well supplied with basic material at the beginning.

CULTIVATION, SOIL REACTION AND NATURE OF ORGANIC PHOSPHORUS

The data in table 1 show that the organic phosphorus content of virgin surface soils is in general considerably greater than that of the corresponding cultivated samples; it has just been said that the reaction of the soil appears

to be without marked influence upon its content of organic phosphorus. The question of the influence of these factors upon the nature of the organic phosphorus compounds of the soil remains to be answered. As a means for detecting any difference in composition which might exist between the organic phosphorus compounds of different soils, the procedure of hydrolysis with 5 per cent sulfuric acid, as used by Jones (3) in his studies of the nucleotides and by Potter and Snyder (5) for ammonia extracts of soil, seemed promising.

The experiment was conducted in the following manner. Eight-hundred-cubic-centimeter portions of the ammonia extracts from the surface soil, both virgin and cultivated, of the pronouncedly acid Wooster loam, the very slightly acid or nearly neutral Clermont silt loam and the alkaline Newton loam were

TABLE 2

Decomposition of organic phosphorus compounds by boiling 5 per cent H_2SO_4

TIME OF HEATING	SAMPLE 4A			SAMPLE 21A			SAMPLE 49A		
	Inorganic P found	Increase due to hydrolysis	Per cent of organic P decomposed	Inorganic P found	Increase due to hydrolysis	Per cent of organic P decomposed	Inorganic P found	Increase due to hydrolysis	Per cent of organic P decomposed
hours	*mgm.*	*mgm.*	*per cent*	*mgm.*	*mgm.*	*per cent*	*mgm.*	*mgm.*	*per cent*
0	2.2	(0.8*)	(15)	1.8	(0.3*)	(8)	1.5	(0.5*)	(8)
½	2.6	0.4	9	2.2	0.4	11	1.8	0.3	5
1:05	2.9	0.7	16	2.3	0.5	14	2.1	0.6	10
2	3.1	0.9	20	2.5	0.7	19	2.4	0.9	15
4	3.3	1.1	24	2.7	0.9	24	2.9	1.4	24
	SAMPLE 5A			SAMPLE 22A			SAMPLE 50A		
0	4.5	(1.0*)	(15)	2.3	(1.0*)	(22)	1.9	(1.2*)	(14)
½	4.8	0.3	5	2.5	0.2	6	2.1	0.2	3
1	4.9	0.4	7	2.6	0.3	9	2.5	0.6	8
2	5.1	0.6	11	2.8	0.5	14	2.8	0.9	13
3¼	5.6	1.1	19	3.1	0.8	23	Lost		

* Increase over that contained in the original solution, due to decomposition during preparation for experiment, including momentary boiling.

allowed to stand in large porcelain dishes for several days, in a place protected from dust but exposed to a constant current of air, until the ammonia had evaporated and the volume was reduced about one-half. The solutions were then transferred to 500-cc. flasks and made to volume with washings from the dishes. Aliquots of 100 cc. were transferred to 200-cc. extraction flasks, sufficient dilute sulfuric acid added to make the solution 5 per cent by weight and reflux condensers attached. The flasks were set, three at a time, upon an electric hot plate and heated as rapidly as possible to boiling, each time starting with the plate cold. After the solutions had boiled the stated time, the flasks were immediately cooled with water, the contents poured into centrifuge bottles, made alkaline with ammonia and treated in the usual manner for the

inorganic phosphorus determination. The results obtained are presented in table 2, also in graphic form in figure 1.

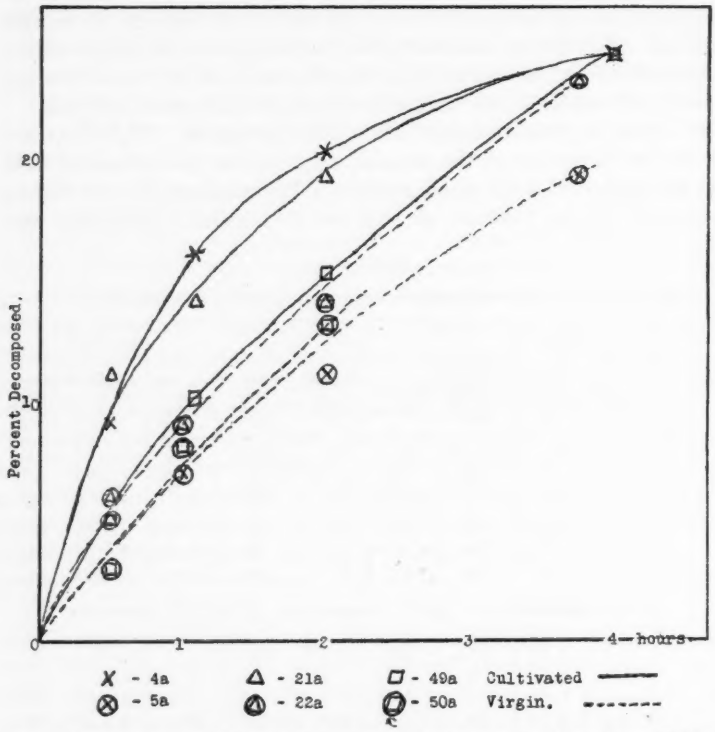

FIG. 1. HYDROLYSIS OF ORGANIC PHOSPHORUS COMPOUNDS BY 5 PER CENT H_2SO_4 AT BOILING TEMPERATURE

In explanation of table 2, it should be recalled that the samples represent 160 cc. of the original extract, and the original contents of inorganic and organic phosphorus were as follows:

SAMPLE	INORGANIC PHOSPHORUS	ORGANIC PHOSPHORUS
	mgm.	*mgm.*
4a	1.4	5.3
5a	3.5	6.7
21a	1.5	4.0
22a	1.3	4.5
49a	1.1	6.3
50a	0.7	8.3

The figures in table 2, enclosed in parentheses, represent increases over the corresponding original amounts of inorganic phosphorus as given above, and the percentage relation of the same to the original organic phosphorus contents. These indicate the amount of decomposition during preparation of the solutions for the experiment, including momentary heating to boiling temperature with immediate cooling, and serve as blank determinations with the time of hydrolysis at zero. Elsewhere in table 2, the amounts of inorganic phosphorus found after boiling for a stated time have been reduced by the corresponding quantities to which reference has been made and the percentages of decomposition have been calculated on the basis of the organic phosphorus remaining undecomposed after this preliminary treatment. These percentages of decomposition are plotted as ordinates in figure 1, while the periods of boiling, in hours, are abscissae.

The data presented in table 2 and plotted in figure 1 indicate that the organic phosphorus compounds of all the cultivated soils are somewhat less resistant to hydrolysis than are those of the virgin soils. It is noteworthy that decomposition during 4 hours' boiling has been precisely the same in the cases of all the cultivated soils, 24 per cent, although the percentages at intermediate periods do not coincide. Of the cultivated samples, the curves representing the acid Wooster loam, 4a, and the slightly acid Clermont silt loam, 21a, show considerable resemblance. Among the virgin samples, the Wooster loam, 5a, shows the greatest divergence from the other two, and also the greatest difference between a virgin and cultivated sample. The alkaline Newton loam shows greatest resemblance between data for virgin and cultivated samples, possibly because its extracts contain most organic phosphorus and any percentage errors are thus smaller. The results of this experiment are so indecisive that extended comment does not seem to be warranted. Neither striking resemblances nor marked dissimilarity among the organic phosphorus compounds of virgin and cultivated soils, both acid and alkaline, is indicated.

AVAILABILITY OF PHOSPHORUS IN ORGANIC COMPOUNDS

While it was not intended to include in this study any reference to the question of the amount of phosphorus supplied to vegetation from that stored up in the organic form, this being a subject for more extended investigation, it may be well to direct attention to some facts disclosed by the data obtained and which seem to furnish indications regarding this phase of the subject. The general relation found to exist between the humus, total nitrogen and organic phosphorus of the soils investigated and the marked similarity of the ratios between these constituents in virgin and long cultivated soils of the same type has been pointed out. The considerable resistance to decomposition by hydrolysis with boiling 5 per cent sulfuric acid shown by the organic phosphorus compounds of all the samples in which this was determined, has been demonstrated. The ready response to phosphorus fertilization shown by

practically all the soils of the state on which fertility experiments have been conducted has been shown by the work of the Ohio Station. Considered together, these facts do not indicate that the phosphorus in organic combinations becomes available very rapidly, certainly not at a generally greater rate than the organic nitrogen associated with it in the soil. Further, it seems altogether probable that the various agencies, including liming and frequent cultivation, known to result in a more rapid utilization of the soil's store of nitrogen, will have a similar effect upon the phosphorus in organic combinations.

SUMMARY

A study of the organic phosphorus content of samples from 12 representative types of Ohio soils, and the relation of the same to other soil constituents, is reported. The observations made have been based upon the examination of virgin and cultivated samples, surface and subsurface, from each soil type considered.

Averaged figures indicate that virgin surface samples are considerably richer in total phosphorus than the corresponding cultivated samples of the same type, and that virgin subsurface samples contain slightly more total phosphorus than cultivated soils at the same depth.

The organic phosphorus contents of the several samples from the average soil type stand in the same order as the contents of total phosphorus.

The organic phosphorus bears very nearly the same percentage relation to the total phosphorus in cultivated soils as in virgin soils at the same depths, in the greater number of cases.

From averaged data, one-third the phosphorus in the surface and one-fifth that in the subsurface samples of both virgin and cultivated soils is in the organic form.

The organic phosphorus and humus soluble in ammonia are shown to be closely related to each other, to total nitrogen in the soil and, to a less extent, the color of the ammonia extract. From averaged data, if 100 represents the percentage of ammonia-soluble humus obtained from a soil, the total nitrogen in the soil is 10, and the organic phosphorus in the ammonia extract is 1. Except as noted, there does not appear to be any connection between other soil constituents and organic phosphorus content.

Reaction of the soil appears to be without influence upon the quantity and nature of the organic phosphorus present.

There is some evidence that the organic phosphorus compounds of cultivated soils are decomposed slightly more readily than are those of the virgin soils examined.

From general considerations, it is thought that the phosphorus in organic combinations in the soil is not of a very high order of availability.

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THE EFFECT OF THE INITIAL MOISTURE IN A SOIL ON MOISTURE MOVEMENT

P. E. KARRAKER

Agricultural Experiment Station, University of Kentucky

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A review of the literature on the effect of initial moisture on moisture movement has been given by Alway and McDole (1). Their statement in this connection is, "No definite conclusions are to be drawn as to the effect of the initial moistness upon movement of water."

Experimental work of their own is also reported. "Seventeen soils, ranging from a coarse sand with a hygroscopic coefficient of 0.6 to a silt loam with one of 13.3, were placed in cylinders in three different degrees of moistness, 0.5, 1.0, and 1.5 times the hygroscopic coefficient, 1 inch of water was applied and the rate of movement during 5 days observed." The percentage of water in the moistened portions at the various times also was determined. It was found that the distance of penetration increased with increase in initial moisture, but that the percentage of moisture in the moistened portions of the soils was no greater, and usually smaller, in the soils of lower initial moistness. The fact that the distance of penetration was less in soils of low initial moistness was evidently due not to a less favorable condition for capillary movement in these soils ahead of the advancing water layer, but to the stronger force with which the smaller amount of water was held within the moistened portion. Had penetration been determined in the presence of a constant supply of gravitational water, no doubt it would have been independent of the initial moisture condition.

Glass tubes were also filled with the same soils in the same three degrees of moistness and the lower ends kept in contact with water at a constant level. Movement up into the soils was generally most rapid in the soils of highest initial moisture, but slowest in those of intermediate moisture condition, so that "no definite dependence of rise upon initial moistness was shown."

Shortly after the date of the above publication, Harris and Turpin reported work on moisture movement, dealing in part with the effect of initial moistness in this connection (3). Their results show that, on the whole, distance of movement is greater in soils of higher initial moistness, particularly when sufficient time is not given for the establishment of entire equilibrium in all soils. Again, however, there is no evidence from their published data of a less favorable condition for penetration of capillary moisture into soils of low initial moistness. The percentage of moisture in the moistened portions of

these soils never increased above that in the moistened portions of the soils of high initial moistness, as would be expected if the dry soil condition presented less favorable conditions for the penetration of capillary moisture than the moist soil condition.

EXPERIMENTAL WORK

Some work was done by the writer at the Michigan Agricultural College during the years 1913 and 1914, on the effect on moisture movement of changes in the surface tension of the soil solution brought about by the addition of soluble salts (4). The salts were mixed with portions of soils. These were then put in short tubes, saturated, and, after percolation ceased, placed in capillary connection with a dry soil underneath. The effect of the salts was determined by weighing from time to time and noting the relative rates at which the differently treated soils gave up water to the soil underneath. The question arose in this connection of the reflex effect on movement of water from the tube soils of differences in the degree of moistening of the soil underneath; for instance, would a tube soil which naturally gave up its moisture slowly be further handicapped on account of the slowness of the moistening of the soil underneath?

A number of laboratory experiments made at the time with two soils—a sandy loam and a clay loam—showed no appreciable effect of differences in initial moistness on moisture movement of water subsequently added. Some of these results, hitherto unpublished, are as follows:

Experiments with sandy loam soil

1. Soil brought to desired initial moisture conditions before being placed in tubes (glass tubes for the most part 2½ inches in diameter, were used in these experiments); same amount of packing given to the two soils; water added to the bottom of the tubes. Movement of water through soil aided by head of water of about 20 cm.
2. Same procedure as in (1) except that the moist soil was packed to a degree to give practically the same apparent specific gravity as that of the air-dry soil.
3. Water added to tops of tubes. A constant head of ¾ inch maintained. Same amount of packing given the two tubes.

Experiments with clay loam soil

1. Water added to tops of tubes, constant head of ¾ inch maintained, soils brought to desired initial moisture content before being placed in tubes.
2. Water added to tops of tubes. Constant head of ¾ inch maintained. All tubes filled with soil of high initial moisture content. Tubes for movement in dry soil reduced to approximately air-dry condition after filling. This procedure was adopted to avoid differences in packing brought about by filling with soils of different initial moisture contents.

With one exception, movement in the air-dry soils was as rapid as or more rapid than in the soils of higher initial moisture content. The exception was a clay loam tube in the first experiment with this soil, where the more rapid movement is probably to be attributed to favorable structural conditions.

TABLE 1

Experiment 1, sandy loam

TIME	DISTANCE REACHED BY MOISTURE MOVEMENT IN	
	Soil containing 5.01 per cent initial moisture	Soil air-dry, 1.00 per cent initial moisture
10 minutes	6.3 cm.	6.8 cm.
35 minutes	11.0 cm.	11.7 cm.
65 minutes	14.7 cm.	15.0 cm.
Total water taken up	272.0 gm.	306.0 gm.

TABLE 2

Experiment 2, sandy loam soil

TIME	DISTANCE REACHED BY MOISTURE MOVEMENT IN	
	Soil containing 5.94 per cent initial moisture	Soil air-dry, 1.00 per cent initial moisture
10 minutes	5.2 cm.	5.5 cm.
30 minutes	9.5 cm.	10.0 cm.
60 minutes	13.3 cm.	13.6 cm.
Total water taken up	290.0 gm.	310.0 gm.

TABLE 3

Experiment 3, sandy loam soil

TIME	DISTANCE REACHED BY MOISTURE MOVEMENT IN	
	Soil containing 6 per cent initial moisture	Soil air-dry, 1.00 per cent initial moisture
10 minutes	4.4 cm.	5.0 cm.
30 minutes	8.7 cm.	9.2 cm.
60 minutes	12.8 cm.	13.0 cm.
Total water taken up	150.0 gm.	178.0 gm.

TABLE 4

Experiment 1, clay loam soil

TIME	DISTANCE REACHED BY MOISTURE MOVEMENT IN			
	Soil containing 8.5 per cent initial moisture		Soil air-dry, 3.5 per cent initial moisture	
	Same amount of packing as air-dry tubes	Packed to give same apparent specific gravity as air-dry tubes	Both tubes packed the same	
minutes	*cm.*	*cm.*	*cm.*	*cm.*
10	5.0	4.5	4.1	3.9
30	9.5	8.0	7.6	7.4
60	13.4	10.9	10.6	10.5
90	16.4	13.1	12.9	12.8

Results with the sandy loam soil showed also a larger amount of water taken up by the soil in the air-dry condition than with the higher initial moistness. On the whole, these results do not indicate any gain in capillary movement in soil due to higher initial moistness.

In the absence of work of a conclusive nature on this point, it seemed desirable to make additional and more accurately controlled experiments along the line of those reported above.[1]

A difficulty in determining the effect of initial moistness on movement of water added is that, in placing the soil of different moisture contents in the tubes, differences in packing result which probably are an important factor in determining the movement secured. To avoid this, specially devised tubes were made of galvanized iron with a portion the entire length removed and a glass plate substituted (fig. 1). This made possible the filling of the tubes with soil of the higher initial moisture contents and, by removing the glass plates and drying, the bringing about of differences in initial moisture content without changing the structural condition. The glass plates also made possible the observation of the distance of penetration of the water film.

TABLE 5

Experiment 2, clay loam soil

TIME	DISTANCE REACHED BY MOISTURE MOVEMENT IN			
	Moist tubes, 6 per cent water added to air-dry soil		Air-dry tubes, 3.5 per cent moisture	
minutes	*cm.*	*cm.*	*cm.*	*cm.*
10	5.0	5.0	4.8	4.5
30	8.0	8.1	7.6	7.5
60	11.2	12.2	11.0	10.8
90	13.6	13.8	14.4	14.2

Four soils were used: a sandy loam, two silt loams, and a clay loam. One of the silt loams was obtained on the station farm at Lexington and will be designated as Station silt loam; the other came from the Purchase Region of western Kentucky, a soil of loessal origin, which will be designated as Purchase silt loam. All four of the soils were surface soils.

The hygroscopic coefficients of these soils are: sandy loam, 2.90; Station silt loam, 5.26; Purchase silt loam, 3.80; clay loam, 7.72.

The soils were used in the following initial moisture conditions: oven-dry, air-dry, hygroscopic coefficient, 1½ times the hygroscopic coefficient, and, in the case of the sandy loam and Purchase silt loam, 2 times the hygroscopic coefficient.

Moisture movement was determined by placing the tubes in a vertical position with their lower ends in contact with water at a constant level and noting the height of rise of water from time to time.

[1] The experiments reported in the remainder of this publication were carried out in the soil laboratory of the Kentucky Experiment Station.

The results are shown in part in tables 6, 7, 8 and 9. Considerable preliminary work was done before the final work reported in the tables. Since the results from this work are in practical agreement with those from the later work, it does not seem necessary to include them. The initial moisture condition of the soil, as well as how it was secured, is shown in the proper headings in the tables. The distance of moisture movement at various times and the final total amount of water taken up are given. The initial percentage of water in the soils as determined by drying in the oven and the apparent specific gravity of the soils also are shown. It will be observed that the

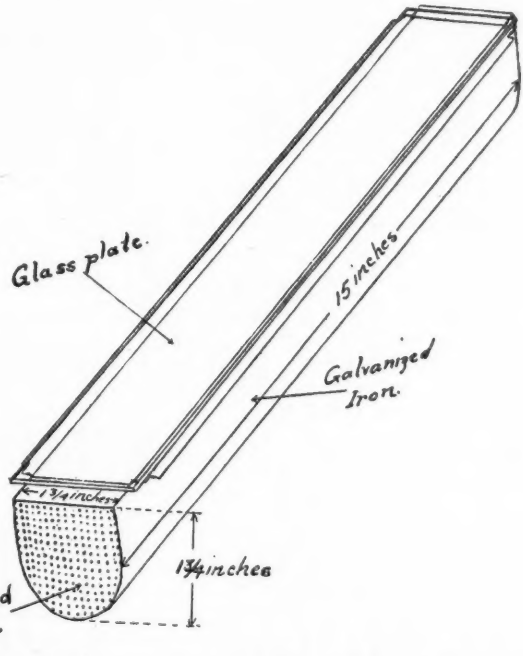

FIG. 1. DIAGRAM OF TUBES ESPECIALLY DEVISED FOR USE IN MOISTURE-MOVEMENT WORK

actual initial moisture condition always varied somewhat from the one desired. Thorough distribution of the initial water added to the soils was secured before putting them into the tubes. The soils were packed in the tubes by adding in small amounts and tamping with a rubber stopper on a glass rod each time before adding a new amount.

From the results given in the tables it is possible to note the effect of initial moisture content on moisture movement in a number of different ways. With the exception of the Station silt loam, no matter how the comparison is made, it is seen that moisture movement was no greater in the soils of higher initial

TABLE 6

Results with sandy loam soil

INITIAL MOISTURE TREATMENT		OVEN-DRY	AIR-DRY TO OVEN-DRY	AIR-DRY DUPLICATE TUBES		HYGROSCOPIC COEFFICIENT	HYGROSCOPIC COEFFICIENT TO AIR-DRY	1½ HYGROSCOPIC COEFFICIENT	1½ HYGROSCOPIC COEFFICIENT TO AIR-DRY	2 HYGROSCOPIC COEFFICIENT	2 HYGROSCOPIC COEFFICIENT TO AIR-DRY DUPLICATE TUBES	
Distance of moisture movement in	20 minutes	5.8 cm.	5.6 cm.	5.3 cm.	5.9 cm.	5.0 cm.	5.5 cm.	5.5 cm.	5.9 cm.	3.6 cm.	5.3 cm.	5.7 cm.
	1½ hours	11.9 cm.	12.0 cm.	11.6 cm.	11.9 cm.	11.2 cm.	11.1 cm.	10.9 cm.	11.5 cm.	7.8 cm.	10.7 cm.	11.0 cm.
	3 hours	15.7 cm.	16.0 cm.	15.8 cm.	16.1 cm.	15.3 cm.	15.0 cm.	14.5 cm.	15.2 cm.	10.6 cm.	13.8 cm.	14.3 cm.
	7½ hours	22.0 cm.	22.6 cm.	23.0 cm.	22.9 cm.	22.5 cm.	21.4 cm.	20.6 cm.	21.5 cm.	15.5 cm.	19.2 cm.	19.6 cm.
	19 hours	29.0 cm.	29.9 cm.	31.3 cm.	31.1 cm.	30.8 cm.	28.5 cm.	27.2 cm.	28.2 cm.	20.5 cm.	24.9 cm.	25.2 cm.
Total water taken up		173 gm.	185 gm.	198 gm.	192 gm.	183 gm.	181 gm.	162 gm.	187 gm.	127 gm.	167 gm.	169 gm.
Initial moisture in soil		None	None	1.17%	1.17%	2.53%	0.81%	4.06%	0.82%	5.72%	0.99%	0.78%
Apparent specific gravity		1.485	1.468	1.464	1.459	1.445	1.440	1.376	1.374	1.331	1.323	1.316

TABLE 7

Results with Station silt loam soil

INITIAL MOISTURE TREATMENT		OVEN-DRY	AIR-DRY TO OVEN-DRY	AIR-DRY DUPLICATE TUBES		HYGROSCOPIC COEFFICIENT	HYGROSCOPIC COEFFICIENT TO AIR-DRY	1½ HYGROSCOPIC COEFFICIENT DUPLICATE TUBES		1½ HYGROSCOPIC COEFFICIENT TO AIR-DRY DUPLICATE TUBES	
Distance of moisture movement in	15 minutes	3.1 cm.	3.2 cm.	3.2 cm.	3.1 cm.	3.5 cm.	3.3 cm.	3.3 cm.	4.3 cm.	3.8 cm.	3.6 cm.
	1½ hours	8.0 cm.	8.2 cm.	7.3 cm.	7.6 cm.	8.6 cm.	7.7 cm.	10.0 cm.	10.5 cm.	9.3 cm.	8.9 cm.
	2½ hours	11.0 cm.	11.2 cm.	10.1 cm.	10.6 cm.	12.1 cm.	10.8 cm.	14.5 cm.	15.0 cm.	13.0 cm.	12.8 cm.
	17¾ hours	27.7 cm.	28.3 cm.	26.5 cm.	27.1 cm.	31.6 cm.	28.5 m.	35.0 cm.	35.0 cm.	31.7 cm.	31.0 cm.
Total water taken up		217 gm.	218 gm.	190 gm.	204 gm.	216 gm.	217 gm.	237 gm.	231 gm.	247 gm.	240 gm.
Initial moisture in soil		None	None	2.56%	2.56%	5.43%	2.67%	7.78%	7.78%	2.34%	2.45%
Apparent specific gravity		1.347	1.335	1.331	1.328	1.258	1.265	1.184	1.192	1.189	1.204

TABLE 8

Results with Purchase silt loam soil

INITIAL MOISTURE TREATMENT		OVEN-DRY	OVEN-DRY TO AIR-DRY BEFORE FILLING	AIR-DRY	HYGROSCOPIC COEFFICIENT	HYGROSCOPIC COEFFICIENT TO AIR-DRY	1½ HYGROSCOPIC COEFFICIENT	1½ HYGROSCOPIC COEFFICIENT TO AIR-DRY	2 HYGROSCOPIC COEFFICIENT	2 HYGROSCOPIC COEFFICIENT TO AIR-DRY
Distance of water movement	10 minutes	3.7 cm.	3.3 cm.	3.9 cm.	4.2 cm.	4.0 cm.	4.9 cm.	5.0 cm.	4.6 cm.	5.5 cm.
	30 minutes	8.5 cm.	7.1 cm.	8.1 cm.	8.7 cm.	8.5 cm.	9.9 cm.	10.4 cm.	9.9 cm.	11.1 cm.
	1⅔ hours	13.4 cm.	11.0 cm.	12.7 cm.	13.8 cm.	13.4 cm.	15.8 cm.	16.0 cm.	15.6 cm.	17.2 cm.
	3 hours	17.9 cm.	14.8 cm.	17.0 cm.	18.5 cm.	18.1 cm.	21.0 cm.	21.2 cm.	20.5 cm.	22.5 cm.
	9 hours	29.3 cm.	23.5 cm.	27.6 cm.	30.5 cm.	29.2 cm.	32.7 cm.	33.4 cm.	31.2 cm.	34.5 cm.
Total water taken up		205 gm.	155 gm.	186 gm.	203 gm.	208 gm.	212 gm.	250 gm.	186 gm.	258 gm.
Initial moisture in soil		None	0.88%	1.43%	3.56%	1.10%	5.40%	1.27%	7.41%	1.33%
Apparent specific gravity		1.438	1.435	1.413	1.321	1.322	1.246	1.254	1.204	1.209

TABLE 9

Results with clay loam soil

INITIAL MOISTURE TREATMENT		OVEN-DRY	AIR-DRY TO OVEN-DRY	AIR-DRY DUPLICATE TUBES		HYGROSCOPIC COEFFICIENT	HYGROSCOPIC COEFFICIENT TO AIR-DRY	1½ HYGROSCOPIC COEFFICIENT DUPLICATE TUBES		1½ HYGROSCOPIC COEFFICIENT TO AIR-DRY DUPLICATE TUBES	
Distance of water movement	17 minutes	2.3 cm.	3.2 cm.	2.1 cm.	1.7 cm.	2.5 cm.	2.7 cm.	3.4 cm.	3.5 cm.	3.6 cm.	3.4 cm.
	2½ hours	7.0 cm.	8.0 cm.	6.3 cm.	6.0 cm.	7.9 cm.	7.7 cm.	9.2 cm.	9.5 cm.	9.5 cm.	9.2 cm.
	17⅔ hours	16.6 cm.	18.5 cm.	16.0 cm.	15.8 cm.	20.2 cm.	19.9 cm.	21.8 cm.	21.8 cm.	22.4 cm.	22.1 cm.
	42⅔ hours	23.9 cm.	26.9 cm.	23.5 cm.	23.5 cm.	29.1 cm.	28.2 cm.	29.9 cm.	29.8 cm.	30 0 cm.	29.7 cm.
	74 hours	30.0 cm.	33.8 cm.	29.4 cm.	29.4 cm.	34.9 cm.	33.9 cm.	34.9 cm.	35.0 cm.	34.8 cm.	34.7 cm.
Total water taken up		238 gm.	277 gm.	225 gm.	228 gm.	250 gm.	277 gm.	224 gm.	217 gm.	283 gm.	282 gm.
Initial moisture in soil		None	None	3.67%	3.67%	8.07%	3.24%	11.87%	11.87%	3.36%	3.54%
Apparent specific gravity		1.310	1.320	1.252	1.309	1.201	1.209	1.119	1.132	1.128	1.114

moisture content than in those of lower moisture content. The hygroscopic water and the presence of an additional amount of capillary water were both without apparent effect in this connection.

The Station silt loam gave no greater movement in the air-dry soil than in the oven-dry soil, but movement was appreciably greater in the soil of initial hygroscopic coefficient and 1½ times the hygroscopic coefficient than in the air-dry soil. Results from preliminary experiments with this soil are also in substantial agreement with this in showing an increase in moisture movement due to the presence of initial amounts of moisture in addition to that in the air-dry soil.

On the whole, however, these results do not show any significant increase in capillary moisture movement due to the presence of small initial amounts of moisture in addition to either the moisture-free or the air-dry condition. Or, stated in another way, neither the air-dry nor the oven-dry soil condition offered any apparent resistance to movement of capillary water through soil as compared with movement in the same soil containing an additional small amount of initial moisture.

It may be called to mind that this has a practical bearing on the necessity of having loose earth mulches in a dry condition for their maximum functioning and also in the application to field conditions of data on the extent of capillary movement obtained by observations made on capillary movement of water in air-dry soils in the laboratory. Some experimental work very often referred to as showing greater capillary movement of water through soil in an initial moist condition than in the air-dry state is that of Briggs and Lapham with movement in dry and saturated sand (2). According to their results, the movement in saturated sand was operative through a distance 4.5 times that in the air-dry sand. It seemed rather reasonable, with this difference in movement in saturated and dry sand, that small differences in initial moisture content in field soils should show an appreciable effect. The fact that such was not found led to the repetition of this work with the dry and saturated sand.

The method of experimentation was practically that of Briggs and Laphan. Distance of movement in the air-dry sand was determined by filling glass tubes of 1-inch diameter with the air-dry sand and determining the maximum height of movement of capillary water from a vessel of water up into the sand; at the same time the maximum height of movement of water through the saturated sand was determined by filling a number of tubes of different lengths with the sand, saturating, and determining the maximum height through which water would be moved to the surface from a vessel of water in contact with the bottom. The fact that movement of water from the vessel to the surface of the sand was taking place could be told both by the sand's remaining moist at the surface and by the drop of water level in the reservoir vessel. The tubes used for determining the distance of movement in the saturated sand usually were of lengths increasing in 5-cm. steps. By remov-

ing the sand as it dried from the top of the tube found to be just above the height of maximum water movement until a permanently moist condition was reached, it was possible to locate fairly definitely within the 5-cm. interval the exact distance sought.

Quartz sand from three different sources was used in this work. (a) The first was sand secured from the Central Scientific Company; it was reasonably clean and in its natural condition gave very good moisture movement. It will be designated as C. S. sand. (b) Second, a sand was secured from the department of chemistry of the Experiment Station, which originally came from some point in Tennessee. This sand appeared clean, but in its natural state gave very poor capillary movement and on examination was found to contain a trace of oily material. It was never used without some preparatory cleaning treatment. This sand will be designated as Tenn. sand. Movement in the C. S. sand was also usually increased by a preparatory cleaning treatment. (c) Finally one experiment was made with a sand from the

TABLE 10

Movement in dry and saturated sand

SAND USED	MOVEMENT IN SAND		RATIO OF MOVEMENT IN SATURATED TO MOVEMENT IN AIR-DRY SAND
	Air-dry	Saturated	
	cm.	*cm.*	
Kentucky River, below 40-mesh	25.5	33.0	1.30
C. S. below 60-mesh	66.0	81.0	1.23
C. S. 40 to 60-mesh	33.0	58.0	1.77
C. S. 40 to 60-mesh	25.0	45.0	1.80
C. S. 60 to 80-mesh	37.3	60.0	1.61
Tenn. 60 to 80-mesh	33.5	48.0	1.43
C. S. and Tenn. mixed, 80 to 100-mesh	41.3	75.0	1.81

sand deposits of the Kentucky River. The sand was used in its natural state. Both the C. S. and Tenn. sand were sieved and portions of different grades of fineness used in the work.

The results from this work are shown in table 10.

The variation between the different experiments makes impossible the assigning of any definite value to the ratio of movement of water in the sand in the two conditions. However, the variation is within reasonably small limits, and while the distance of movement is greater in the saturated than in the dry sand, yet the average ratio between the two of 1.56 shows a very much smaller increase in the saturated condition than that found by Briggs and Laphan

SUMMARY

Soils were placed in specially devised tubes and different initial moisture conditions brought about. These tubes were set in vertical positions with their lower ends in water, and the distance of penetration of water at various

times determined. It was found that small differences in initial moisture content of the soils were for the most part without significant effect in this connection, the distance of movement being as great in the oven-dry or air-dry soil as in soil containing an additional initial small amount of water.

A repetition of the work of Briggs and Laphan with movement in dry and saturated sand showed that movement in the saturated sand as an average of a number of experiments was 1.56 times that in the air-dry sand.

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